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Simulation Of Tactile Roughness Using Ultrasound Haptics

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Abstract

Virtual reality experiences can be made more immersive with the use of haptic technologies. However, the current methods rely on bulky controllers and gloves that only offer basic vibrations to differentiate textures. This thesis proposes a new approach that utilizes ultrasound haptics and various techniques to create a sense of roughness. The research conducted explores different parameters for inducing roughness and their compatibility with ultrasound haptics. A new technique for eliciting varying levels of roughness using basic patterns is also introduced. To compensate for the lack of physical object and textural information, two studies were conducted using audio and visual modalities. The findings reveal that basic patterns can successfully simulate roughness through ultrasound haptics, but some traditional roughness-inducing parameters do not work. Additionally, visuals have a minimal impact on roughness perception, and audio does not positively affect it.

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Declaration

With the exception of chapters 1, 2 and 3, which contain introductory material, all work in this thesis was carried out by the author unless otherwise explicitly stated.

Chapter 1

Introduction

1.1 Motivation

Tactile sensation plays an instrumental role in the emission of information. As a sensory input, tactile feedback is quite limited and varies between body parts. However, the information provided by the varying mechanoreceptors of the skin is enough to inform of the necessary information, such as feeling pointy, scratchy, pulsating or tickly. At this moment, media started its slow shift towards a virtual world through the use of virtual reality headsets, immersing its users in the three dimensions through their point of view. Even though virtual headsets are quite adequate at outputting high-fidelity visuals and audio, they lack the necessary tools for conveying high-quality haptic feedback, specifically tactile feedback. Current solutions to tactile feedback take the form of controller vibrations and vibrating or force-inducing gloves, all of which are hard to instrument. Lacking instrumental modalities, such as haptic can have deteriorating effects on the experience of a user within a virtual reality setting, specifically around the concept of presence within the VR. Presence, the illusion of a person existing in a VR world even though he knows that he is not [6, 7], is directly related to the number of high-quality modalities existing within a VR setting. VR requires high-quality haptics, however, at the moment that is not entirely possible, because it requires the haptics to be able to be generated on demand and be of sufficient quality. This entails that there is a requirement of a haptic apparatus that can convey haptics, without impeding the user within the VR setting while emitting haptic sensations.

Ultrasound haptics can solve the issue mentioned above by enabling three-dimensional tactile feedback that does not require user instrumentation. Ultrasound haptics allow the generation of tactile feedback points (known as focal points) at any uninhabited location in a three-dimensional space [8]. Focal points are areas of sound pressure in the desired loci, whose modulation allows the emission of a variety of sensations (e.g., varying amplitude [2, 8] or position [9]). The focal points can move at high speed and require no additional user input. Methods have been developed for creating basic haptic shapes [9–11] using ultrasound haptics; however, most applications use the presence of focal points to simulate contact with a virtual object (e.g., [8, 12–15]). The reason behind this simplistic interaction with this technology is due to its generally weak force feedback, low resolution and the low number of simultaneous focal points. In order to bypass the limitation imposed by the technology, this thesis will present two methodologies that will enable focal points to act and move in specific patterns in such a manner as to mimic real textures or simulate the feeling of roughness.

There are multiple forms of haptics that a human can experience, e.g. roughness/smoothness, hardness/softness, wetness/dryness, stickiness, slipperiness, coarseness and others [16]. Roughness is the perception of tactile properties of a surface touched by a person, which also depends on how it is touched [1]. Roughness is the most prevalent form of haptic feedback studied in the scientific community, some of them depicting parameters responsible for conveying varying levels of roughness or techniques to simulate varying levels of roughness [17–19]. Given the aforementioned reasons and the ability of ultrasound haptics to seamlessly allow the study of roughness mediating parameters such as amplitude, groove width, inter-element spacing, and speed, roughness will be the haptic percept that will be studied in this thesis.

This thesis will also gauge the effect of audiovisual modalities when combined with the previously mentioned methodologies in order to bridge the loss of information generated by the weak force feedback of the focal points and lack of tangible material. In order to bridge the loss of information, virtual models will be used to enrich the interaction of the users. The use of virtual visual objects allows the production of a more realistic haptic experience. The realization of a realistic virtual object is commonly achieved by introducing it to relevant technologies such as virtual and augmented reality [12, 14, 15]. Additionally, the generation and application of audio-synthesized cues will be studied since audio can help modulate tactile perception [20–23]. The audio-synthesized cues will express roughness by altering roughness-conveying parameters such as loudness [24–26] and higher frequency attenuation [27].

1.2 Thesis Statement

The thesis statements assert that ultrasound haptic feedback enables the generation of techniques that can simulate the material roughness of a real object. Ultrasound haptic feedback allows the generation of non-tangible, short-range, high-speed focal points, enabling the synchronised integration of audiovisual modalities. However, ultrasound haptics have a weak shear force that can promote the loss of important tactile information. To compensate for the loss of tactile information, this thesis studies the audiovisual modality integration of multiple tactile feedback techniques by addressing their roughness-conveying abilities.

1.3 Contributions

The contributions of this thesis advance the field of ultrasound haptics, with particular emphasis on the simulation of tactile roughness. This work has not only expanded theoretical understandings but has also delivered practical applications and methodologies for enhancing the integration of ultrasound haptics into virtual reality and associated technologies.

Initially, this research deepened the comprehension of texture perception facilitated by ultrasound haptics. It critically assessed apparatus-specific parameters, such as Hand Traversal Speed (HTS), and evaluated haptic acuity differences between ultrasound-generated sensations and traditional tactile feedback mechanisms. This nuanced understanding aids in refining the application and effectiveness of ultrasound haptic systems.

Moreover, the work systematically evaluated the efficacy of traditional roughness-mediating parameters within the context of ultrasound haptics. By investigating these parameters, the thesis presents a foundational analysis of how conventional haptic feedback mechanisms translate into the domain of ultrasound technology.

Additionally, this thesis developed a technique for producing ultrasound-generated sensations that exhibit varied levels of roughness. This technique represents a significant step forward in the design and implementation of nuanced haptic feedback systems, providing a methodological basis for future works.

Lastly, the research fills a critical gap in the existing literature by explaining how audiovisual modalities influence ultrasound-generated haptic sensations, particularly in scenarios devoid of solid material. This exploration into multimodal feedback systems offers pivotal insights for the development of more immersive and realistic virtual environments.

1.4 Research Questions

This thesis aims to answer the following questions:

> **RQ1:** How does the Hand Traversal Speed of an ultrasound focal point improve the discrimination of realistic textured surfaces?
>
> **RQ2:** How do changes in speed, focal point number, movement direction, and inter-element spacing affect perceived roughness scores?
>
> **RQ3:** Does the use of basic ultrasound haptic patterns such as circles, lines, and dot arrays accurately simulate textures of varying levels of roughness?
>
> **RQ4:** How do audio-visual modalities improve roughness perception of ultrasound-generated sensations?

1.5 Research Design and Rationale

To address the aforementioned research questions, this thesis employs a combination of quantitative and qualitative methods. Specifically, the research design includes:

1. **Texture Discrimination Studies**: These studies will investigate realistically textured surfaces to understand texture perception in a tangible context.
2. **Two-Interval Forced Choice Study (2IFC)**: 2IFC aims to examine roughness-mediating parameters, providing insights into how different variables influence the perception of roughness.
3. **Magnitude Estimation Studies**: Two separate studies will focus on the roughness-mediating capabilities of mid-air patterns, exploring how these non-tangible textures are perceived in terms of roughness.

In the field of haptics, discrimination studies are a method of experimental research that attempts to determine the smallest detectable difference between two stimuli. In this thesis, the stimuli are the detection of tactile feedback that varies in roughness levels. Discrimination methodologies are great at providing insights into the sensitivity of participants to various tactile stimuli and can provide quantitative data that offers multiple avenues for statistical analysis. However, discrimination studies are easily affected by individual variabilities, can be very cognitively demanding and do not offer any insights into the reasons a subject chose one option over the other. Discrimination studies are chosen specifically for realistically textured surface studies within this thesis because they offer the ability to understand the thresholds of the different textured surfaces.

2IFC studies are another great tool for studying haptics. 2IFC studies employ two intervals that contain a stimulus and require participants to indicate the interval that presented a particular feature. These studies are great for haptics due to forcing a choice, which in turn reduces response biases and guessing, it produces easy-to-interpret results, and these types of studies are highly sensitive. However, 2IFC, just like texture discrimination can be cognitively demanding, can induce training effects and offer little information on cognitive or neural decisions. 2IFC was chosen for this thesis due to its high sensitivity which is important when measuring tactile parameters in isolation and because they are one of the most commonly applied methodologies in haptics.

Magnitude estimation is a psychophysical method used to quantify subjective perceptions by having participants assign numerical values to the perceived intensity of stimuli. This method is commonly employed in sensory research, including studies on tactile perception. Just like the previous methodologies magnitude estimation provides highly sensitive data, however, it also provides flexibility to participants to score as they feel, without being forced into specific values. Even though this methodology requires some training and introduces the complexity of continuously comparing input feedback to a numerical value, magnitude estimation is a great tool for studying mid-air patterns because it provides very rich data to infer results.

Finally, while not listed as a primary methodology, it is important to recognize the limitations of the aforementioned techniques. The methodologies described are effective in addressing specific research questions by analyzing quantitative data. However, they do not account for the cognitive processes or potential biases of participants. To gain deeper insights and contextual information regarding participants' cognitive processes, this thesis often complements these methods with post-study semi-structured interviews or surveys. These qualitative approaches, sometimes accompanied by thematic analyses, provide valuable perspectives from the participants, enriching the understanding of the data and highlighting cognitive influences that quantitative methods alone cannot capture.

1.6 Thesis Structure

1.6.1 Chapter 2: Literature Review

In this chapter, the literature used for this thesis will be explored. The goals include providing a clear understanding of the motivation behind the thesis, explaining how the research questions were developed, and outlining the methodologies used to answer these questions. To achieve this, the basics of haptics and ultrasound haptics will be covered, the impact of secondary modalities like pseudohaptics, audio, visual, and VR technologies will be discussed, and details on the experimental designs necessary for the research will be provided.

1.6.2 Chapter 3: Texture Mediating Parameters for Ultrasound Haptics

This chapter presents two studies investigating the effects of multiple roughness-mediating parameters available to ultrasound haptics. These studies target contributing some answers to **RQ1** and answer **RQ2**. The studies cumulatively explored seven parameters: Hand Traversal Frequency, Haptic Acuity, Speed, No. Focal Points, Movement Direction, Focal Point Parameters Distance and Inter-element Spacing. The scenarios tested are on textured surfaces that are comprised of realistic details, and each parameter is in isolation. Later chapters build from the results of the studies, as mentioned earlier.

1.6.3 Chapter 4: Roughness Simulation Using Mid-Air Patterns

In this chapter, a methodology for simulating roughness using mid-air patterns is introduced. It combines the findings from Chapter 3 to create patterns that can convey roughness perception at varying levels. The goal of this chapter is to address RQ3. A study is conducted on five patterns at two different levels of speed magnitude, resulting in a total of ten patterns being explored.

1.6.4 Chapter 5: Multimodal Interaction with Mid-Air Textured Surfaces

This chapter studies the effects of audio-visual modalities. The studies in this chapter contribute an answer to RQ1 and answer RQ4. Chapter 5 covers Studies 4 and 5, which investigate the effects of audio and visual stimuli integrated with mid-air textures and mid-air patterns.

1.6.5 Chapter 6: Conclusions

This chapter forms the conclusions of this thesis by summarising the results of the studies and reflecting upon the initial research questions. It also discusses the limitations of the works described in this thesis and informs of possible future works in this area of study.

1.7 Overview of Experiments

This thesis presents five experimental studies that aim to contribute to or answer the research questions mentioned in Section 1.4. Table 1.1 shows that two studies focus on modulable parameters of ultrasound haptics, one study shows the combined results of the parameters in the creation of a roughness-conveying methodology and finally, an audio-visual modality integration in mid-air textured surfaces.

Topic	Study	Research Questions	Context and Purpose
Texture Mediating Parameters	1	RQ1, RQ2	Investigate the efficacy of *Hand Traversal Frequency* of a focal point and the effect of *Haptic Acuity* in mid-air textured surfaces.
	2	RQ2	Investigate the efficacy of Speed, *No. Focal Points, Movement Direction, Focal Point Distance* and *Inter-element Spacing* in isolation.
Roughness Simulation	3	RQ3	Study the roughness-conveying ability of mid-air *Patterned Sequences*.
Multimodal Interaction	4	RQ1, RQ4	Study the effect of *audio* and *visual* modalities on mid-air textured surfaces.
	5	RQ2, RQ3, RQ4	Study the effect of *audio* and *visual* modalities on mid-air patterns.

Table 1.1: Table shows which studies cover which topic, the associated research questions and a contextual explanation of what was studied.

Chapter 2

Literature Review

This chapter focuses on the literature review that influenced the direction of this thesis. It begins by defining the fundamental properties of haptic perception and distinguishing between texture and roughness perception. The goal is to determine which of these concepts would be better suited for conveying material composition through haptic feedback in Ultrasound Haptics. Additionally, the literature will discuss Ultrasound Haptics, a tactile feedback methodology that can supplement the limitations of current virtual reality technologies' tactile components.

The chapter will also delve into the concept of pseudo-haptics, which deals with unintended haptic experiences that can be used to create new haptic feedback techniques. It will explore the use of additional auditory and visual roughness modalities and their effect on haptics through varying mediums. Moreover, the literature review will explore Virtual Reality, its uses, and how haptic methodologies are currently represented in it. It will also discuss the limitations of these methodologies and the standard experimental designs used in haptics, reporting their applicability and use in the field.

2.1 Haptic Perception

As defined by Lederman S. J. [16], haptic perception of a textured surface is defined as the perceived percepts of roughness/smoothness, hardness/softness, wetness/dryness, stickiness, slipperiness, coarseness and others. Lederman and Klatzky [1] explain that haptics is a perceptual system which is compromised of two subsystems: the cutaneous and the kinesthetic. The kinesthetic subsystem allows the ability to perceive one's body position, movement orientation/ speed/ agency and weight [28, 29]. The cutaneous, or tactile, system allows the recognition of inputs from the mechanoreceptors and thermoreceptors under the skin [1]. These receptors are spread across our skin, just under the epidermis. Focusing on the cutaneous system is essential since the kinesthetic system does not impact the perception of texture. Given the aforementioned previous work, it is important for tactile feedback to focus on stimulating the cutaneous system of a person's skin. Specifically, a tactile feedback apparatus should target the excitement of the mechanoreceptors, instead of the thermoreceptors.

Haptic exploration is the methodology and techniques with which a subject manipulates and senses an object or a surface to identify its haptic properties. Examples of such explorations are lateral motion, unsupported holding, pressure, enclosure, static contact, and contour following (visualised in figure 2.1). Lederman *et al* [1], explain that the haptic perceptual system typically requires proactive exploration, however, passive haptic perception can also provide haptic information to a lesser extent. Proactive exploration entails a user actively running their finger or palm over and around an object. In contrast, passive perception describes a palm either resting on a surface or letting the surface travel over the subject's palm. By passively touching an object, subjects turn their focus to their subjective bodily sensations. Instead, during active exploration, subjects focus their attention on the external details of the object, assessing all cutaneous inputs.

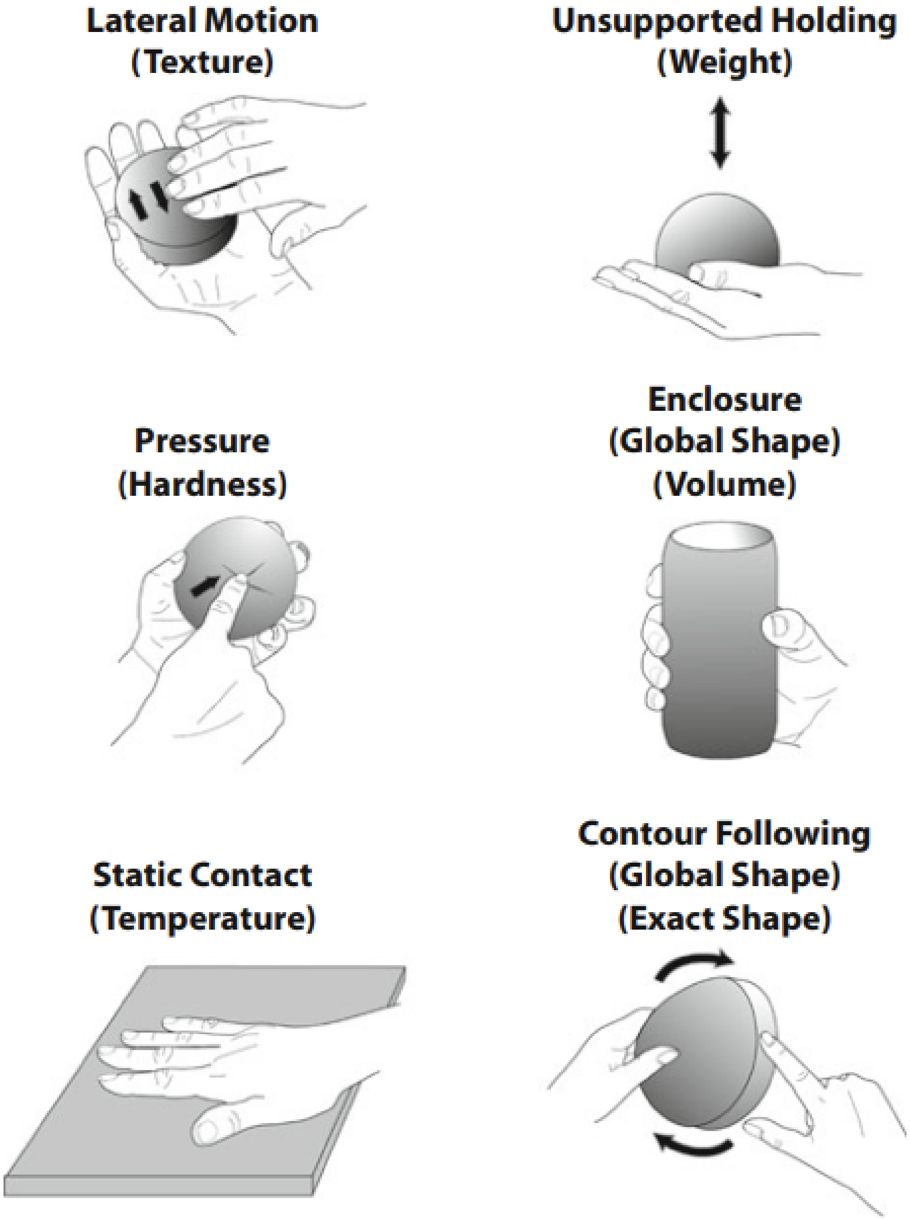


Figure 2.1: Visualisation of procedures of exploring haptic attributes on objects. [1]

Every tangible object can be described by combining information using different factors. These factors can be identified as thermal quality, compliance, weight, geometric properties, orientation and surface texture [1]. Thermal quality characterizes the apparent warmth/coolness upon contact between a human's skin thermoreceptors (which can discriminate temperatures between 5°-45°C) and an object. Typically contact is achieved by touching using the palm (regular temperature of 25°-36°C [30]) and an object. The experimental settings that were followed were set up in a laboratory setting in which the temperature was within the average room temperature margin, which is within the upper and lower margins for tactile discrimination.

Compliance describes the deformability of an object under pressure. Compliance has been researched by Srinivasan *et al* [31], where whilst investigating the tactual discrimination of softness between objects, some of their results identified that compliant objects show continuous indentation under pressure whereas the rigid objects deform up to some critical point and then compress. Weight can reflect the density and structure of an object, typically by allowing the object to rest on a motionless palm. Proactive events, such as wielding and lifting, enhance the ability to determine weight [32]. Compliance is a limitation of this thesis, as explained in the previous chapters, the studies within this thesis use contact generated from focused ultrasound, essentially modulated air pressure. There is not enough sheer force to imitate the weight or compression of the supposed surface. This is something that needs to be taken into account when discussing the results of the studies.

Geometric properties of objects are typically divided into two scales in regard to type and shape: the properties that can be distinguished between the area of a fingertip which can reveal shape by skin indentation and the properties that extend beyond the fingertip where shape perception is constructed by the accumulation of kinesthetic inputs [1]. In regard to orientation, it has been stated that horizontal and vertical lines are haptically perceived better than oblique lines [33]. When attempting to convey tactile sensation to a participant, it is essential to accommodate the use of the whole palm, thus allowing exploration of fine details through the use of the fingertips and allowing subsequent judgement to be made by the accumulated information from the rest of the palm. Additionally, any generated tactile texture or pattern should be purposefully orientated either vertically or horizontally, to accommodate the palm's ineffective perceptual resolution when exposed to oblique contours.

2.1.1 Roughness

Roughness is the percept that reflects the properties of the surface touched with the manner in which the surface is manually explored [1]. Roughness has received the most attention from haptic researchers [34–39] because roughness is a well-defined concept in the haptic research community which enables a wide area for research. The work of this thesis focuses on using various methodologies in order to simulate roughness-conveying sensations on the palm. In this thesis, two themes regarding texture simulation will be explored: the simulation of roughness characteristics and the stimulation of mechanoreceptors.

The desire to create a roughness-conveying methodology is not unique. Researchers such as Zhao L. *et al* [17], Holmes E. *et al* [18] and Potier L. *et al* [19] have been successful at reproducing successful roughness-conveying methodologies. However, it is necessary to understand the factors that characterize roughness. Taylor M. M. and Lederman S. J. in a series of studies have concluded that the gap between the elements that constitute the surface and the width of the elements of a surface are important factors that affect perceived roughness [40–42]. In particular, a narrow groove or increased land mass in a grooved surface will reduce perceived roughness. Another finding from their studies is that variation of the applied finger force during the exploration of a grooved surface can alter roughness perception, meaning that the manner in which a surface is explored can alter perceived roughness. In the context of ultrasound haptics - a weak and low-resolution haptic interface - it is expected that there will be a greater distance required to show similar results.

Another critical parameter is the spatial distribution of the textural elements, rather than temporal factors [34, 35, 37, 43]. Furthermore, the amplitude of force has been found as a determining factor in enhancing the perceived roughness [38, 44]. It should be noted that neither changing hand speed during exploration [45] nor emitting low and high frequencies at a fingertip alter the perceived roughness [16]. Finally, it has been noted that in a passive setting, the speed of actuation and the inter-element spacing of actuation enhances the perceived tactile perception [46]. The aforementioned works set a number of parameters that can be studied, such as amplitude, groove width, inter-element spacing and speed on a passive setting. Ultrasound haptics allow the manipulation of those parameters by effortlessly generating focal points with different speeds and locations.

The idea that we can target specific mechanoreceptors in order to produce specific tactile sensations is not novel. Blake D. *et al* supported the idea that slow adapting mechanoreceptors (type I) are responsible for conveying form and texture, whereas the fast adapting mechanoreceptors are responsible for flutter, slip and motion sensations across the skin [47]. However, varying works have categorised the individual mechanoreceptors' primary functions. E.g. sustained pressure at low frequencies ($<$5Hz) [48] or spatial deformation [49] can stimulate slow adapting type I mechanoreceptors such as the Merkel complex where one of the primary functions is the perception of coarse texture [47]. Additionally, the mechanoreceptors whose primary function is to enable fine texture perception are the fast adapting type II Pacinian corpuscle [48] which can be stimulated with temporal changes in skin deformation ($\approx$40 to 400Hz) [50]. Ultrasound haptics allows the stimulation of the necessary frequencies in order to stimulate both the Merkel complex and the Pacinian corpuscle which enables the generation of areas that can convey fine or coarse textures.

2.1.2 Summary

To summarize the key points, this thesis focuses on the cutaneous subsystem for conveying texture through the use of ultrasound haptics, which stimulate mechanoreceptors to produce sensations of both smooth and rough textures. The studies will be conducted in room temperature laboratories, emphasizing proactive exploration to enable the discovery of finer textural details. The research will involve subjects using their palms and fingertips to achieve a comprehensive tactile perception. Although compliance studies are not feasible due to technical constraints, the investigation will seamlessly explore variables such as amplitude, groove width, inter-element spacing, and speed using ultrasound haptics. Specifically, groove width will be examined through focal point distance and inter-element spacing.

2.2 Ultrasound Haptics

Iwamoto *et al.* [2] has first demonstrated in 2008 how to produce non-contact haptic feedback by utilizing airborne ultrasound. His method employs a nonlinear phenomenon of ultrasound acoustic radiation pressure (P). Iwamoto *et al.* explain they can control P's spatial distribution by using wave field synthesis. Furthermore, their study explains that by applying airborne ultrasound on the human skin, the skin reflects 99% of the ultrasound, which enables two conditions: a) Unlike a previous study [51], there is no need for a mediator reflective film to reflect the ultrasound, and b) the sound energy is converted directly to P. To induce tactile feedback, Iwamoto *et al.* used an array of 40 kHz transducers (n = 100) that shot a burst of P on the user's palm, whose frequency was modulated between 20 Hz and 250 Hz (figure 2.2 shows a sample array). The single point of tactile feedback is referred to as a *focal point*. Constant P application was also used, but the users felt only the onset and offset of the radiation pressure. Finally, the evaluation of their study has shown airflow around the area of contact, which was considered acoustic streaming. Iwamoto's work has enabled the application of ranged tactile feedback that requires no user instrumentation and does not force the tactile feedback recipient to wear unnecessary equipment. The tactile feedback emitting methodology mentioned above is referred to as "ultrasound haptics".

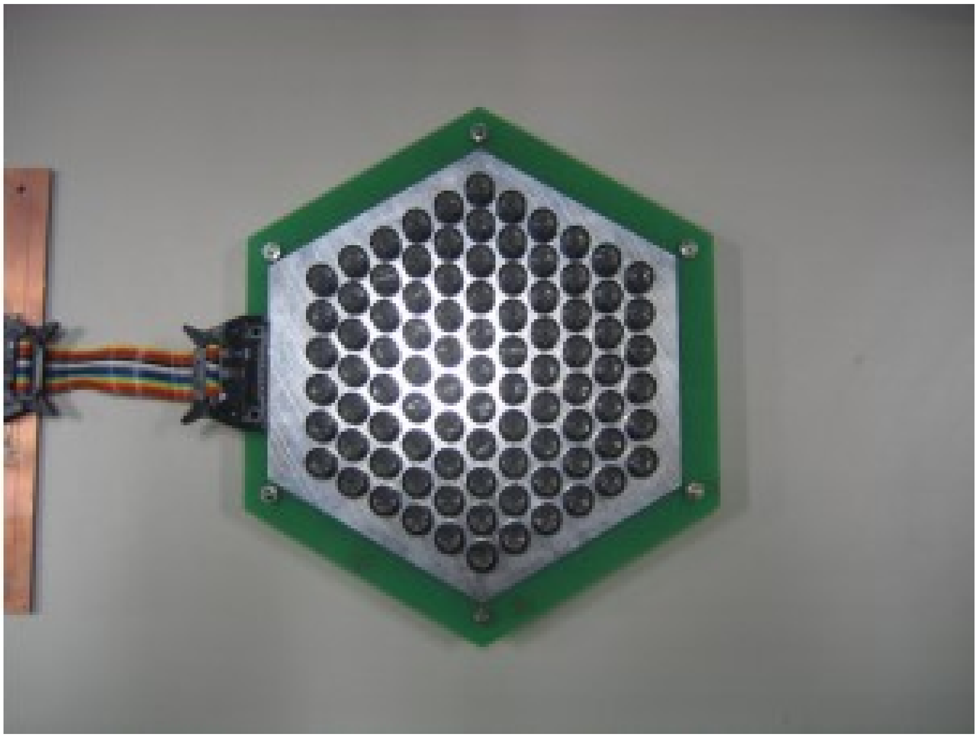


Figure 2.2: The front side of an annular array of airborne ultrasound transducers. [2]. Reproduced with permission from Springer Nature

Ultrasound haptic feedback primarily targets the Pacinian Corpuscle (PC) receptors, which respond to rapidly repeating onset of pressure [52]. These are stimulated by repeating signals at a rate of 40–400 Hz [53]. Studies involving lower modulation frequencies [9, 54] suggest focal points may also stimulate the Meissner Corpuscle (sensitive to 5–40 Hz signals). It is important for this thesis that ultrasound haptics are able to stimulate a wide range of mechanoreceptors, so any tactile sensations are clearly presented on a subject's palm.

Jason A. et al. [55] developed two methods for generating multiple focal points in 2011. The first method is named "spatial multiplexing" it focuses on splitting the array of transducers into multiple sets within the array itself. This method allowed the generation of secondary wave-field maxima that interfered constructively between them causing the production of additional regions of haptic feedback, i.e. additional focal points. The second method, called "temporal multiplexing" created the perception of multiple focal points by having one focal point of 40 kHz revolve a set amount of times around multiple loci. The circling over one locus created the perception of a singular focal point in the center of the circle. By comparing the two methods "temporal multiplexing' is the best suited for tactile feedback output because it can provide more focal points and is not limited by the number of available transmitters in the array. The ability to emit multiple focal points is important to this thesis because it broadens the range of sensations that can be created by allowing simultaneous multi-finger stimulation.

Carter T. *et al.* [8] investigated in 2013 the desirable properties of their *UltraHaptics* display and demonstrated the ability of that system to generate multiple, localized, focal points. *UltraHaptics* can create multiple focal points by multiplexing scenes with different numbers of focal points. The software's algorithm takes step-by-step each scene, calculating the phases and amplitudes of each transducer, taking into account any constructive interference. This technique allows the generation of multiple focal points with varying frequencies. Their studies focused on focal point discrimination, where users were asked to discriminate between zero, one or two focal points at different frequencies (4, 16, 63, 250 Hz) and different separation lengths (1, 2, 3, 4 and 5 cm). The results showed that greater lengths increased discrimination accuracy and that the discrimination increased further by ensuring the two focal points had different frequencies.

2.2.1 Advantages

Ultrasound haptics provides a solution that other haptic systems struggle with solving. E.g. ultrasound haptics enables non-contact vibrotactile feedback, i.e. the user not touching a real object but instead the feedback experienced is airborne. Other tactile transmitting methodologies focus on the users wearing a tactile actuator, either in the form of a glove [56] or strapping vibrotactile stimulators on the users' fingers [57]. Such methodologies provide unnecessary haptic feedback before the actual haptic stimulation.

Other haptic conveying systems rely on bulky robotic arms and complicated control methods to convey on-demand tactile feedback to the unadorned palm [58]. In comparison, ultrasound haptics requires an array of transducers to convey haptic feedback from a distance. Other solutions that succeed in conveying non-contact tactile feedback are air jet systems [59] which suffer from two drawbacks: a) they are unable to produce localized feedback due to diffusion, and b) they suffer from low bandwidth [2, 60].

2.2.2 Use Cases

Ultrasound haptics is used to create three-dimensional shapes [11] by controlling the volumetric distribution of the acoustic radiation inside a force field. The three-dimensional shapes have been shown to have high discriminating and identifying accuracy by users, but required the shape to be within the working volume of the device in order to work as intended, it could only work on the palm efficiently, and there was a limitation to their device array size and power.

Furthermore, ultrasound haptics was utilised in the generation of surfaces, where Freeman E. *et al.* [39] presented the generation of mid-air textured surfaces. A haptic surface is defined as the tessellation of three-dimensional shapes in a plane. In order to produce the surfaces, a continuous check of mid-air hand position is conducted, which upon an intersection with a hand, provides ultrasound haptic feedback at the intersected points. In order to produce a simultaneous feeling of the feedback points throughout the hand, a haptic feedback point iterates the intersected points at high speed.

2.2.3 Limitations

Carter T. *et al.* [8] demonstrated with a pre-user study evaluation that by increasing UltraHaptics focal points the strength of the focal points is reduced (1 focal point = 726.6dB, 2 = 71.7dB, 3 = 68.2 dB, 4 = 67.4 dB and 5 = 66.6 dB). Additionally, Carter T. explains that generating a focal point of pressure creates a focal point with a diameter of 1cm (i.e. the wavelength of the sound at 40 kHz) and emphasizes the need for a minimum 1cm distance between two focal points due to the need of a low-pressure area between them. The minimum focal point distance issue does not originate from a hardware limitation, but instead, it represents the hand's incapability to distinguish the two points at smaller distances.

2.2.4 Summary

Ultrasound haptics represent a non-contact methodology that modulates acoustic radiation pressure to generate tactile feedback in the form of focal points. The literature identifies two primary methodologies for producing multiple focal points: spatial multiplexing and temporal multiplexing. Temporal multiplexing is the preferred approach due to its reduced hardware limitations and the capacity to generate a greater number of focal points. The innovative hardware interface, UltraHaptics, has successfully adopted ultrasound haptics, thereby mainstreaming the production of multiple focal points through its advanced hardware capabilities, and it will be the system with which this thesis will produce ultrasound haptics.

2.3 Pseudo-haptics

Pseudo-haptics are haptic illusions generated as a result of the exploitation of the brain's capabilities and limitations by using a collection of techniques, systems, and approaches that attempt to either simulate a property of what something "feels" like, or use visual models to simulate some haptic quality [61–64]. By definition, Pseudo-haptics are generally split into two categories: Unified Percept Stimulation where the stimulation of a unified percept of a specific haptic environmental property is attempted and Visuo-haptic Stimulation where the effects rely on visuals to induce haptic properties [61]. In this section, we discuss both of those categories. The pseudo-haptic area of study is of interest in this thesis because it provides knowledge of unintentional after-effects from multi-loci tactile stimulation, and informs of how visuals can produce intentional or unintentional consequences.

2.3.1 Unified Percept Stimulation

Unified percept simulation attempts to stimulate a unified percept in a way as to enable the user to actually feel "it" (e.g. [65, 66]). E.g. attempting to simulate the compliance of an object by modulating the force and displacement [66] of a Spaceball from Spacetec [67]. Two pseudo-haptic effects that are important to this thesis are Apparent Tactile Motion (ATM) and Phantom Tactile Sensation (PTS).

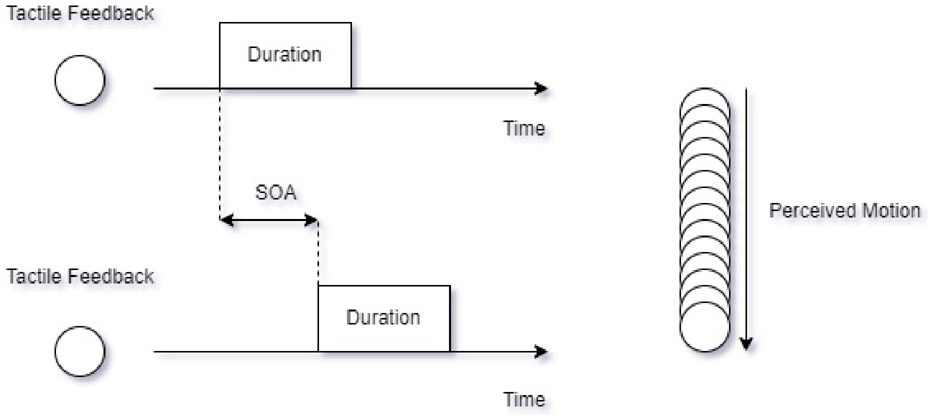


Figure 2.3: Representation of Apparent Tactile Motion and the involved parameters. Each circle represents a tactile feedback point, rectangles are the duration of feedback, SOA is the inter-stimulus onset asynchrony, and the perceived motion line shows how the user perceives the movement in actuality. Recreated from Tactile Brush: Drawing on Skin with a Tactile Grid Display [3]

ATM is the phi-phenomenon that allows the user to perceive motion when two tactile feedback points are sequentially presented in close proximity along the skin [68]. ATM's model is dependent on two parameters: a) stimuli duration, the duration of each tactile stimulus and b) inter-stimulus onset asynchrony (SOA), i.e. the time that the second stimulus starts after the first stimulus is actuated [69] (see figure 2.3 for a representation of ATM). Kirman J. H. explains that for a subject to perceive movement, the tactile stimulus duration should be less than 200ms as increasing duration decreases the perception of movement. Kirman J. H. also explains that SOAs follow a power function based on the duration, and speculates that the type of tactile stimuli can affect the optimal SOA values [70]. Sherrick's and Roger's type of stimuli is of the vibrotactile type, the same as ultrasound haptics. Their results suggest optimal SOA for a 150ms duration is 140ms (using 150ms duration since that is the optimal duration for ultrasound haptics to be felt consistently).

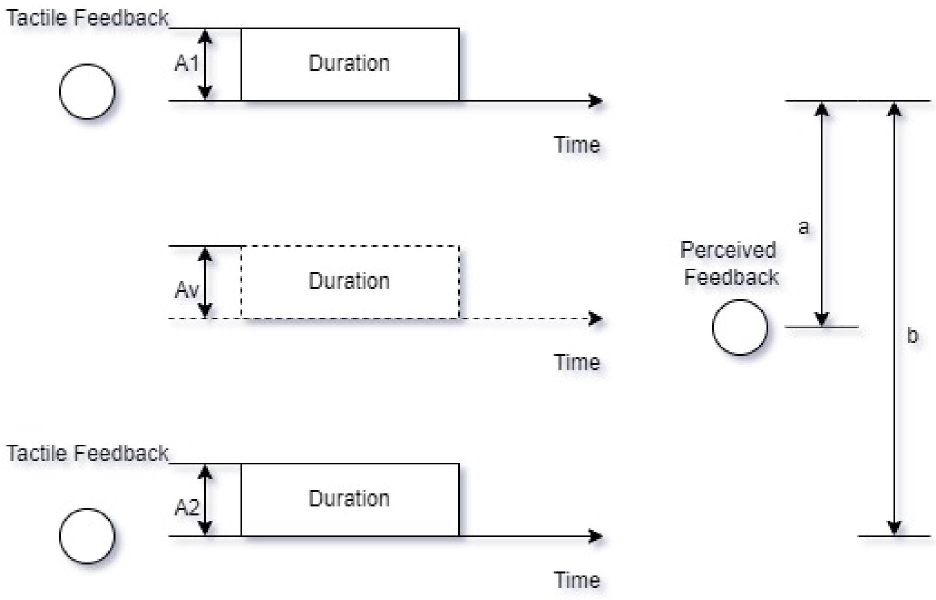


Figure 2.4: Representation of Phantom Tactile Sensation and the involved parameters. Each circle represents a tactile feedback point, rectangles are the duration of feedback. A1/A2/Av are the intensities, and a and b are the distances from the top. Recreated from Tactile Brush: Drawing on Skin with a Tactile Grid Display [3]

PTS is a pseudo-haptic phenomenon that describes the event that which two haptic actuators that are in close proximity actuate simultaneously onto skin, the user instead of feeling two discrete tactile feedback points, feels only one motionless point in the middle of them [71, 72]. PTS is both a tool and a limiting factor, e.g. it can be a limiting factor when generating fast tactile sensations in close proximity and PTS can create unwanted tactile sensations. However, PTS can be used as a tool, since the middle tactile sensation's intensity can be controlled by modulating the absolute intensity of the two actual stimuli.

2.3.2 Visuo-haptic Stimulation

Visuo-haptic stimulation relies on the cognitive interpretation of a visuo-haptic simulation, i.e. it can infer the feeling of touch by exposing a user to visual stimuli [3]. Visuo-haptic stimulation has been found to be a better alternative to mechanically simulated haptics, featuring better performance measures, lower error rates and high satisfaction rates. However, it is not enough to replace haptic feedback [73]. Visual techniques such as visual resizing of virtual objects could be used to convey sensations of bumps [74]. The most important visuo-haptic effect for this research is the expectation effect. The expectation effect is the misconception of a user into asserting the haptic properties of an object from visual stimuli [75]. The expectation effect can be used to create immersive virtual objects when combined with haptics or produce the feeling of surprise to a user who does not expect the difference. The understanding of how the expectation effect affects the results of visuo-haptic experiences can be used as a tool for understanding the results of studies related to this field.

2.3.3 Summary

Pseudohaptic phenomena can facilitate the simulation of surfaces and elucidate discrepancies between intended and perceived tactile sensations. Apparent Tactile Motion (ATM) refers to the perception of movement generated by sequential tactile stimulation. For ATM, values will adhere to a duration of 150 ms and an inter-stimulus onset interval (SOA) of approximately 140 ms. Phantom Tactile Sensation (PTS) is the phenomenon of creating a phantom sensation at the midpoint between two distinct tactile stimuli. PTS can be instrumental in modulating the intensity of feedback and in interpreting distance-related results. The expectation effect, which involves inferring the haptic properties of an object from visual stimuli, can enhance the development of visual models for multi-modal studies.

2.4 Multimodal Interaction in Haptics

Lederman explains that texture is multisensory, i.e. regardless of the attributes of a texture, we use haptics, vision and audio in order to perceive [76]. Therefore, it is necessary to explore additional modalities when investigating a texture parameter such as roughness. The necessity derives from the need to understand the human capabilities in the field of human-computer interaction regarding the new modality, in this case, ultrasound-generated, mid-air textures. The additional modalities that will be investigated are audio and video, the most commonly used modalities, whose common status is the product of their high information throughput.

2.4.1 Audio & Haptics

Firstly the connections between audio and haptics will be explored. The study of the effects of audio on haptic experiences can date back to 1932 when Paul von Schiller [20] stated the possibility of noise bursts or tones (at regular intervals) may affect the tactile perception of roughness. Since then, this theory has been researched in more detail. V. Jousmaki *et al* [77], have researched the aforementioned concept - audio affecting tactile perception - and conducted a study in which they asked their participants to rub their hands and recorded the resulting sound. The recorded sound was modified in order to dampen or accentuate its high frequencies (over 2kHz) over a +-15dB range. His results have shown that accentuating the high frequencies correlate to the haptic feedback feeling smoother or dryer but when dampened the feeling was rougher or moister.

Although the effects of V. Jousmaki *et al* certainly suggest a correlation between audio and haptic perception, the audio that was used was relevant to the context of the action since sounds were recorded and then reused for the same task. A different approach has been researched by Suzuki Y. *et al* regarding the effects of task-irrelevant sounds on the tactile perception of roughness. The results of their studies conclude that task-irrelevant audio cues affect perceived roughness but the effects only occur in a limited range of tactile surfaces or when using appropriate roughness and audio combinations. The single most significant audio was white noise, which led to rougher auditory percepts, whereas pure tones led to smoother auditory percepts [22].

Difilippo, D. *et al*, explains that a contact interaction is the act of a person manipulating a physical object. At the moment of contact interaction, audio and physical forces are produced that communicate to the user information about the relationship between the object and its surrounding environment. An example would be the scenario of sliding a coffee mug on a table. The movement of the mug over the table provides the user with information (through audio) regarding the texture and composition of both the table and the mug [23]. Their results emphasize the necessity for sound to be a byproduct of touch, i.e. the subject consciously decides to move their arm, touching a surface and then expecting the produced sound to inform them of the haptic qualities of what they touched. For this reason, any audio-synthesized cues will be produced only during contact with some form of a visual surface.

2.4.2 Visual & Haptics

The combination of haptic modalities with visual displays is a common phenomenon in research. In 1998, Plesniak & Pappu [78] have developed a coincident visuo-haptic work-space, composed of a Phantom haptic device and MITś second-generation holographic system, which enabled users to interact and feel a holographic object. Their study is motivated by the fact that an item in real life has a close relationship between its material and the skilled eyes, hands and intuition of a craftsperson. Their work has derived a series of rules for visuo-haptic interfaces to obey:

- "The volumes of real or virtual objects should not interpenetrate"
- "occlusion, stereopsis, and motion parallax cues should report the same depth relationships"
- "visual and force images of objects should have “stable” spatial and temporal properties (no perceptible temporal intermittence, spatial drift, or wavering)"
- "optical and haptic material properties, as represented, should be compatible (a surface that looks rough shouldn’t feel soft and spongy)"
- "all multisensory stimuli should appear to arise from a single source, and all should be in precise spatial register"

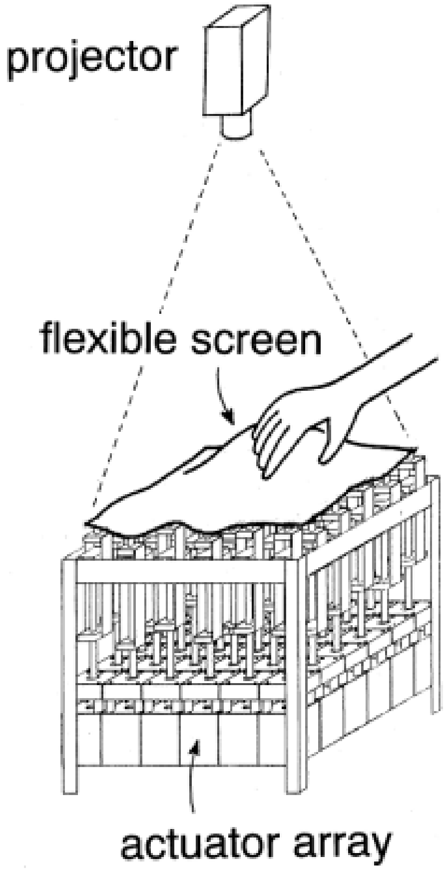


Figure 2.5: Representation of the basic idea of the FEELEX. Extracted from Project FEELEX: Adding Haptic Surface to Graphics [4]

The idea of creating a visuo-haptic work-space has been studied again in 2001 by Iwata *et al* [4]. Their idea was to develop a construct that enabled users to feel with their own hands a continuous surface which resembles an image, thus enabling visual and haptic sensation simultaneously. Their goals were achieved by developing an array of rods (the haptic actuators) where a flexible fabric rests on top of them onto which an image is projected (see figure 2.5). This model represents the need for actual hands being used in the events of a haptic experience as it enables the ability to palpate an unreal three-dimensional surface.

In 2004 Gunn *et al* [79], constructed a remote surgical master class using a haptic virtual environment. Since system lag was again an issue for this scenario, Gunn *et al* have developed a specialized physics model that could withstand latency up to 200 milliseconds. Part of their results has shown that the haptic interaction during the organ manipulation in the surgical masterclass was subjectively, very helpful although no quantitative results were presented. After 2004 an increasing amount of studies emerged that tried to combine video-haptic scenarios, such as the haptic video scenario by Saga S. *et al* [80], haptically annotated movies by Gaw D. *et al* [81] and the development of HapSeat by Danieau, F. *et al* [82].

2.4.3 Summary

The modulation of high frequencies in audio can significantly alter the perception of auditory roughness. White noise is particularly effective in inducing the sensation of roughness. The production of sounds during tactile interaction is essential. According to the work of Plesniak and Pappu, a series of guidelines that this thesis will adhere to when presenting a visuo-haptic interface. Furthermore, it is crucial to present the hands of a subject during the roughness perception of a visual modality.

2.5 Visual Roughness

Haptic textures can be described by the magnitudes of their varying parameters, such as groove width, height, and inter-element spacing [1]. Unlike haptic textures, visual textures are based instead on the patterned contrast variations over a visual surface [83], where the variations are smaller than the display itself [84]. Furthermore, visual textures can pre-attentively describe texture element depth by utilizing a texture gradient [85], different textural elements can lead to the segregation of regions in a two-dimensional image. These pre-attentive features are called “textons” and the groupings of similar “textons” are the foundation of visual texture areas [86].

2.5.1 Visual roughness in haptics

By using “textons,” one can aim to create textures areas that can have a specific roughness. Ho *et al.* [5] showed that modulating the visual roughness of a two-dimensional image is to represent a texture that is being shined upon an angle. The angled light source creates shadows in-between intermittent peaks and valleys, and the proportion of shadow size is a determinant factor of roughness (see figure 2.6). This information was used in both multimodal studies to create the rendered images of the 3D models.

Figure 2.6: Representation of the sandpapers with varying grit but equal luminosity direction. How direction of illumination affects visually perceived surface roughness [5]

Visuals play a significant role when they are combined with roughness. Initial studies found that in isolation, visual modality is better at matching the roughness of an object [87], but later studies showed that both modalities could judge roughness equally [88–90]. However, when the two modalities combine there is a weight combination as to which percept provides the most information most reliably [91, 92]. However, the literature is not concrete on whether the weight is towards the haptics or the visuals. There is evidence of touch being the more contributing factor [93, 94] but there is literature suggesting that visuals bring biases that affect the outcome [83, 95, 96]. Finally, there is an agreement that texture perception involving visuals and haptics are complimentary and independent [97].

2.5.2 Summary

Visual roughness is influenced by the perception of shadows. This relationship will be thoroughly examined within the thesis to understand how shadow perception contributes to the overall sensation of surface texture. Visual elements can impact haptic perception by leveraging the participants' biases, a factor that will be explored to determine how visual cues can be manipulated to alter tactile experiences. Among various modalities, the touch modality holds the greatest weight when used in conjunction with visual stimuli. This finding underscores the importance of integrating tactile feedback in visuo-haptic interfaces, a key focus area of the thesis.

2.6 Auditory Roughness

Audio is typically capable of conveying auditory roughness by modulating the inter-element spacing of a traversed groove, but in isolation audio alone is worse at determining material roughness [98]. Even though sound can provide some roughness information when touch is available, it is ignored, or its effect is negligible [99]. A parameter that can affect the roughness percept of a sound is loudness [24–26].

Furthermore, modulation of frequency and amplitude can heighten the perception of smoothness/dryness [77] and specifically the augmentation of high frequencies can promote smoothness when heightened and roughness when attenuated [27]. However, even though audio can affect perceived roughness when it is combined with haptics, the weighted contribution is 38% for audio and 62% for haptics [100].

2.6.1 Summary

Using different loudness levels can convey varying feelings of roughness. This aspect will be investigated within the thesis to determine how changes in loudness affect the perception of surface texture. The ability to modulate perceived roughness by adjusting the higher frequencies of an audio cue will also be examined, providing insights into how audio modifications can influence tactile sensations. Among various sensory modalities, the touch modality holds the greatest weight when used in conjunction with audio cues. This finding highlights the critical role of tactile feedback in multisensory experiences, which will be a central theme in the thesis.

2.7 Virtual Reality

Virtual Reality (*VR*) is the set of technologies that enable a person to experience computer-generated content (audio, visual, haptic, etc.) in a simulated world, whether it is real or not [101]. Virtual reality can take the form of digital content on one or more traditional computer screens, can be projected on walls such as the CAVE [102], or experienced through a head-mounted display with technologies such as Oculus Quest 2 [103] or Valve Index [104]. VR used to have difficulties approaching the general population due to the requirement of heavy and expensive equipment that had difficulties presenting high-quality graphical content at a good performance. However, with today's VR technology, a user can experience seamless, high-definition visuals, with high-fidelity audio which enables various interactions with the virtual world. A VR system is drastically distinct from traditional media by encompassing the following three key features: *Immersion*, and *Presence* and *Interactivity* [101].

2.7.1 Immersion

Immersion is the concept defined as "the user's engagement with a VR technology that results in being in a flow state" [7]. The definition of *Immersion* has been expanded and generalised over time; however, the central concept remains the same, i.e. *Immersion* encapsulates the computer-generated media (e.g. audio, visual, haptic) that stimulate the users' senses with the purpose of persuading the users that the vivid environment they experience is authentic. *Immersion* literature showed that VR Immersion improved search task performance against traditional interfaces and has shown a positive transfer of training from VR to stationary displays [105]. Therapists use *immersive* VR as a tool to treat phobias, such as acrophobia [106], by exposing patients to simulated phobia-inducing scenarios in VR. *Immersive* VR is used as a safer and cheaper alternative to train military personnel by navigating the troops through a virtual representation of a city [107].

In order to successfully immerse a user in the virtual world, a VR system and the accompanying generated content through it must be able to output a high level of sensory fidelity, i.e. visual, auditory, and any other additional sensory cue [108]. Enforcing high-fidelity modalities aids in ensuring the user experiences the real-world (not necessarily the real world). The better a simulated world matches the real one, the greater the perceived Immersion. Thus, the thesis needs to simulate as realistically as possible any additional modalities when exposing a user to a VR environment to increase the user's immersion.

2.7.2 Presence

Presence is the perceptual concept of when a user experiences the illusion of existing in a VR world even though he knows that he is genuinely not [6, 7]. E.g. as Slater M. [6] explains, the perceptual system of a user may recognise and respond against a threat while the cognitive system catches up after the reactionary response. The definitions of *presence* and immersion are sometimes used interchangeably due to describing the user's state when interacting within a VR experience; however, it is crucial to understand that where immersion describes the fidelity of the modalities experienced by a user, *presence* details the subjective psychological response towards those modalities. The psychological response that users do emphasises the need to develop a *presence* within a virtual environment because when a user believes that he exists in an environment, he can then react to events as if they were real [109] . Presence is vitally important because presence has been shown to increase task performance and therapy outcomes in VR settings [110–112]. Given that this thesis intends to project multiple roughness-conveying techniques which can be hard to understand conceptually, and given the lack of real objects, ensuring optimum levels of presence will be vital to help participants not experience the dissonance between real life and virtual environment.

Wallach S. *et al.* [113] explain that there are three categories of variables that can influence perceived *presence*: Technological, User and Interaction variables. Technological variables describe how technical details, such as the VR hardware itself and its modalities, can help improve *presence*. User variables focus on how user personalities, cognitive abilities, anxiety levels, ethnicities and gender influence *presence*. Interaction variables describe the interaction between the user and VR hardware and how those interactions can affect *presence*. The subsections below detail the technological and interaction variables and will omit the user variables due to them diverging from the focus of the thesis.

Technological Variables

Earlier studies [113, 114] suggest that discordant elements have a crucial role in influencing *presence*. Discordant elements are defined as elements within a virtual environment that are discordant with the user's everyday experiences. Such elements can attract the focus and can disturb users' experience. Therefore, it is essential that a VR imitates everyday life and ensure the removal of discordant elements from within the virtual environment.

Vividness of imagery, i.e. the degree of sensory richness in a virtual setting [115] increases *presence* [115–117]. Vividness can be influenced by modulating the sensorial breadth (number of sensory dimensions employed) and sensorial depth (degree of resolution in each sensory dimension) of the stimuli conveyed to a user. These variables can affect the involuntary attention a subject allocates within a virtual environment [118]. Also, increasing the number of sensory modalities improves *presence* [119], as long as the modalities are congruent with each other [118]. The sight modality is the most prevalent at influencing *presence* which may be because our visual cortex comprises 70% of our cortex [120].

Furthermore, ensuring the use of a wearable VR helmet instead of a traditional TV screen [121] and making sure the VR wearable technology is not cumbersome [122] will increment *presence*. Finally, eliminating interface transparency (i.e. helping the user consciously disregard the VR equipment) and eliminating distractions throughout use can improve *presence* [123].

2.7.3 Interaction Variables

Interactivity is the degree to which a user can interact and manipulate the content or design of an environment [117]. Both the user's focus of attention and the increased involvement from interaction within a virtual environment can directly improve the perceived *presence* [124]. A learning task study by Persky, *et al.* [125] found that active control over a virtual environment resulted in higher levels of presence against a group that passively experienced the same environment, and the team expressed that it is the body movements that are responsible for the increase in the presence and that the bodily movements are more important than the realistic depictions of environment details. Riva G. [126], expressed that a virtual environment that wants to enable presence should allow the user to engage in action while granting the possibility of successfully completing it. Usoh *et al.* found further evidence which showed that users that walked had greater levels of presence scores in comparison with users that walked in place [127]. Finally, a virtual environment that allows interactions with its users should also try to enforce intellectual or emotional meaning with the environment in order to induce *presence* [128–130].

2.7.4 Limitations

Although VR can improve the media experience of a user, it also bears some limitations which can cause discomfort to users and obstruct future development. VR is an inhibitor of motion sickness, eye fatigue, headache, nausea, and sweating [131–133]. Space Motion Sickness (SMS) is different in VR in comparison with natural motion sickness, due to the fact that the user does not have to move for SMS to occur. SMS is prevalent in VR and can be caused by distinct head movements [133], e.g. for an upright sitting user head movements such as pitching or rolling can have greater SMS provocation rather than yawing [134,135]. In order to reduce SMS occurrence it is reasonable to reduce the rate of head movement during a VR interaction.

General eye fatigue is caused by a high rate of change of the two biological responses of the human eyes when the eyes are trying to focus: accommodation and vergence [136]. Accommodation is the process of when the eye lenses are flexed in order to focus an image on the retina. Vergence is when the eyes rotate inwards to create a singular binocular image. To reduce general eye fatigue, a user should reduce those two processes, therefore a virtual environment should reduce the necessity of changing the depth of field of a user. Further discomfort to the eyes can be caused due to the eyes being enclosed within a warm vacuum caused by the overheating display of the VR hardware and can be avoided by establishing frequent and on-demand breaks [131].

2.7.5 Summary

Virtual Reality (VR) technology is readily available and capable of producing high-fidelity content, a factor that will be crucial in the thesis to explore the potential of VR in various applications. VR is distinct from traditional media due to its characteristics of immersion, presence, and interactivity. Immersion, defined as the sum of sensory stimuli that allow the user to experience authentic scenarios, will be examined to understand its role in creating realistic VR environments. The thesis will also investigate how realistic additional modalities in VR contribute to increased immersion.

Presence, described as the illusion of existing within a VR environment, is vital for enhancing user experience. Improving presence aids in persuading users to interact realistically within VR, an aspect that will be explored to optimize user engagement. Methods to improve presence include removing discordant elements, enhancing imagery vividness, minimizing the visibility of VR hardware, and reinforcing interaction.

Interaction, which describes the user's ability to engage with elements within a VR environment, will be analyzed for its impact on user involvement and presence. The thesis will examine how increased interaction through enabling interactive events and establishing intellectual or emotional meaning with these interactions can improve user experience.

However, VR can cause discomfort to users by eliciting motion sickness, eye fatigue, headache, nausea, and sweating. Therefore, strategies need to be implemented within VR-related works to minimize discomfort, such as reducing frequent changes in the depth of view, minimizing head movement, and establishing frequent and on-demand breaks. These insights will guide the development of VR systems that maximize user comfort and engagement while minimizing adverse effects.

2.8 Experimental Design

2.8.1 Two-alternative Forced Choice

Two-alternative Forced Choice (2AFC) is an experimental methodology that presents the subject with two choices of a modality and the user is forced to choose which choice most represents an aforementioned criterion. The order in which the choices are presented is randomised from trial to trial. The subject is not allowed to choose both choices or none of them. 2AFC requires both choices to be simultaneously presented, and at the end of the choice presentation, the user must make the choice. 2AFC is usually can be split into either detection tasks or discrimination tasks. The detection tasks focus on the subject identifying, within the two choices, whether some sensory input existed, thus detecting the input. In the discrimination tasks, the subject focuses on which choice was the most extreme stimulus. Forced choice experiments are useful in determining absolute thresholds (detection tasks) and difference thresholds (discrimination tasks) [137]. This is due to their exceptional session-to-session variability [138], high level of performance, and because 2AFC discourages response biases [137, 139, 140].

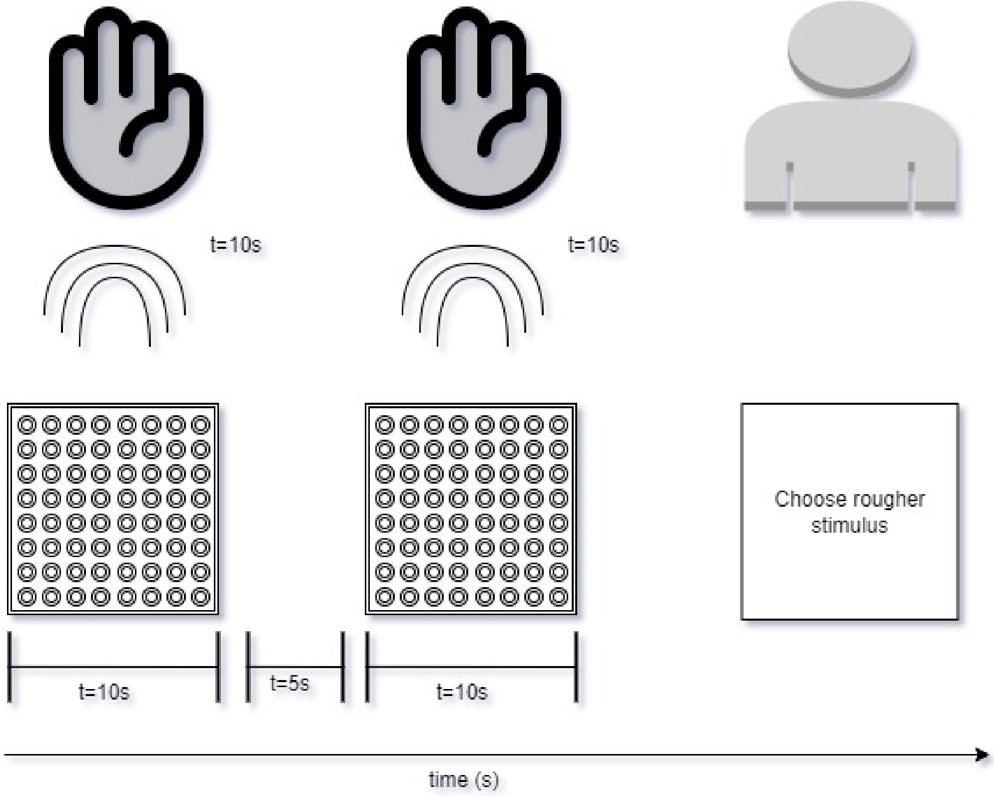
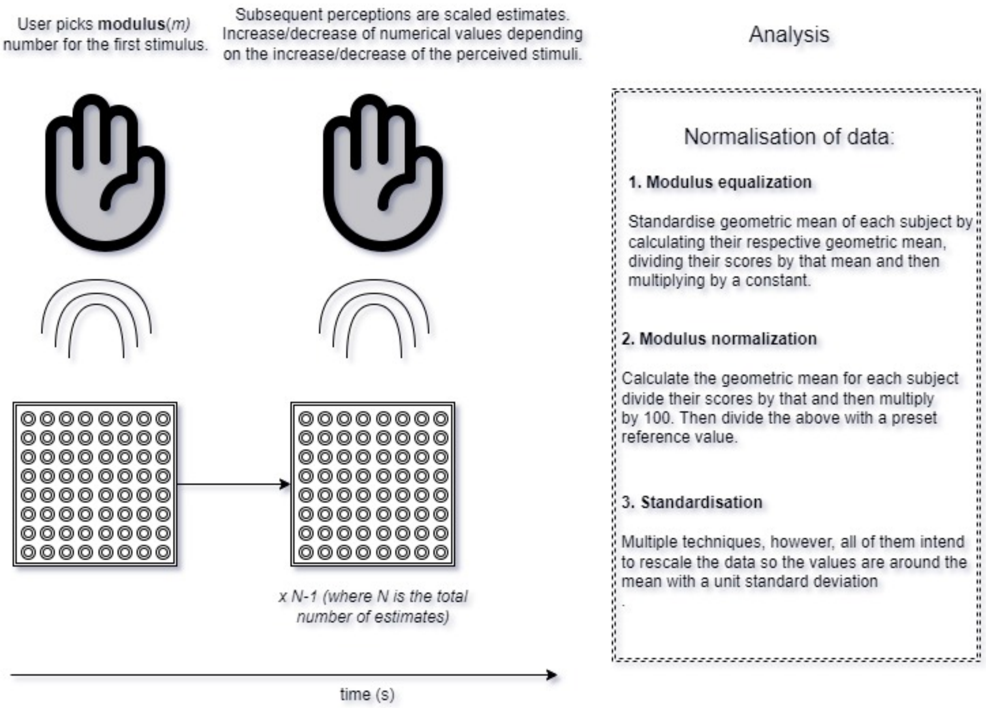


Figure 2.7: Representation of the general procedure for a subject to perceive two tactile stimuli and then choose the rougher one.

The studies that will follow will be mainly discrimination tasks, where a user given a set of tactile stimuli, will choose which stimuli felt rougher. Furthermore, the experiments will focus on two-interval forced choice (2IFC), a variation of 2AFC that presents both choices sequentially, rather than simultaneously [137, 141]. The reason for using 2IFC is due to the lack of both equipment availability and equipment capability (e.g. the Ultrahaptics array cannot perform multiple tactile sensations with the expected intensity simultaneously). Generally, the studies will have the subjects perceive one choice of tactile stimuli for approximately 10s and then a second one for another 10s (the time between two stimuli is approximately 5s), and finally, the subject will be forced to discriminate which tactile sensation felt rougher (see figure 2.7).

2.8.2 Magnitude Estimation

Magnitude estimation is a method used in psychophysics which allows the freedom of subjects partaking in a study to provide their own values against a certain stimulus thus enabling the collective ratios of numbers to reflect the ratios of the stimuli (see figure 2.8). This methodology was first introduced in studies of naive (unpracticed) subjects by S. S. Stevens from Harvard University during the 1950s. The results from those studies show that a repeatable logarithmic function emerged, unaffected by the size of the magnitude estimates and possessed ratio-scale properties. Subsequent studies verified that magnitude estimation produces reproducible scale values with ratio scale properties [142]. In haptics, multiple studies use magnitude estimation as their preferred experimental methodology [143–146], because it disallows predefined maximum and minimum values while taking into account the inexistence of a stimulus. Additionally, in relation to this thesis, magnitude estimation was also used for studying ultrasound haptics [147–150].



User picks **modulus**(*m*) number for the first stimulus.

Subsequent perceptions are scaled estimates. Increase/decrease of numerical values depending on the increase/decrease of the perceived stimuli.

x N-1 (where N is the total number of estimates)

Standardise geometric mean of each subject by calculating their respective geometric mean, dividing their scores by that mean and then multiplying by a constant.

Calculate the geometric mean for each subject divide their scores by that and then multiply by 100. Then divide the above with a preset reference value.

Multiple techniques, however, all of them intend to rescale the data so the values are around the mean with a unit standard deviation

Figure 2.8: Representation of the general procedure for a subject to attend a magnitude estimation study.

Magnitude estimation can be performed with a relatively low amount of subjects (8 to 40). Each subject is expected to be provided instructions on how to perform the estimation, and these instructions can affect the resulting data. There are two approaches for instructing magnitude estimations, instructed and non-instructed. Instructed requires the subjects to provide numbers that describe the ratio of sensory intensity, e.g. given two sensations where one is rougher than the other by a ratio of two times, then the subject should respond with the number 2. Non-instructed allows the participant to be free to enumerate the sensory input to a number, leaving the ratio calculation to the researcher, e.g. given two sensations where one is rougher than the other by a ratio of two times, a subject can assign a value of 50 to one of them and 100 to the other. In this thesis, the latter, the non-instructed approach will be used, because it allows greater flexibility and makes no assumption of ratios existing in the first place [142, 151].

The first estimation a subject provides is called the modulus (m) and the way the m is presented is important to avoid biases and round-number tendencies. Two important scenarios could cause issues during the analysis of the results. The first important scenario is when the first sample is very high or low level, this can cause issues by enforcing bias to higher or lower estimations. The second scenario is when the initial sample is the same for all subjects which given some of the subjects use the same starting estimation could cause a bias to that number (e.g. half the subjects starting with 50). If the subjects are naive, then presenting them with m that within a middle range can surpass some of the aforementioned issues. However, to avoid these issues in general it is suggested to randomize the presentation of all the samples as well as the initial one [142].

Performing a holistic analysis of numbers with different minima and maxima is illogical and that is why it is required for a transformation of that data to be performed. The transformation should generally focus on normalizing the data, thus making the values of the dataset have a common scale but avoiding loss of information. There are generally three common ways for magnitude estimation to achieve data normalization: *modulus equalization*, *modulus normalization* and *standardisation*. Performing *modulus equalization* requires the calculation of the geometric mean for each subject and then diving all estimations of that subject with the geometric mean and finally multiplying that by a preset constant. *Modulus equalization* requires non-zero estimation in the dataset. *Modulus normalization* similarly requires the geometric mean for the dataset to be calculated and multiplied by 100, however, a predefined set of internal reference values between the different types of samples is required to be generated. During analysis for a specific sample requires the division of the score with the preset internal reference value. *Modulus normalization* requires the variety of samples to be ordinal, in some way, so a preset internal reference value can be properly calculated. *Standardisation* aims to restructure the dataset so that its values are centered around the mean and scaled (typically from 0 to 1). To circumvent the existence of studies that do not have clearly defined ordinal samples and not be forced to use non-zero values, *standardisation* seems to be the preferred normalization method.

2.8.3 Summary

The two-alternative forced choice (2AFC) is an experimental methodology where subjects must choose one of two given options. This thesis' studies will employ the 2AFC paradigm for discrimination tasks, providing a rigorous framework for evaluating subject responses. Additionally, the studies will utilize a variation of 2AFC known as two-interval forced choice (2IFC), which presents the two choices sequentially rather than simultaneously. This approach will be crucial in examining the temporal aspects of decision-making in our experiments.

Magnitude estimation is another experimental methodology that allows subjects to freely adjust the scale of their estimation based on previous inputs. This technique is widely used in ultrasound haptics research and will be adopted in our studies for its flexibility and adaptability. The non-instructed approach inherent to magnitude estimation will enable subjects to provide more natural and varied responses, avoiding strict ratio assumptions and enhancing the robustness of our data.

To minimize biases, the initial estimation m and subsequent samples will be randomized. This randomization is essential for maintaining the integrity of the experimental results. During the data analysis stage, a standardization procedure will be performed to normalize the data, ensuring comparability across different subjects and conditions. These methodologies will form the backbone of the experimental design, facilitating a comprehensive investigation into the tactile and perceptual phenomena under study.

Chapter 3

Texture Mediating Parameters for Ultrasound Haptics

3.1 Introduction

Recreating the perception of roughness with non-contact technologies, such as ultrasound haptics, requires more complex tactile interaction with the users. The lack of touchable material disallows users from experiencing genuinely rough sensations. To bypass the need for touchable material, it is required for an understanding of how texture-inducing parameters can affect roughness perception with non-contact texture perception technologies, such as ultrasound haptics. Understanding how each of those parameters affects roughness, can be used as a tool for designing more roughness-accurate, non-contact textures.

This chapter aims to study a series of parameters that are available to ultrasound haptics. The parameters are Hand Traversal Frequency (HTF), Tactile Acuity (TA), focal point speed, direction, focal point number, focal point distance and inter-element spacing.

First, in this chapter, the study of TA and HTF is done by using the methodology developed by Freeman E. *et al.* [39]. The methodology presents a technique for producing realistic textures by providing a mathematical formula describing the texture. The methodology requires an array of transducers and a Leap Motion sensor. The Leap Motion Sensor uses infrared light to recognise the location of the hand and quantifies it in XYZ axes. The array of transducers used in this chapter is the Ultrahaptics Evaluation Kit 1 - Dragonfly (figure 3.1) . The software collects the location/coordinates of the palm and an approximation of its bones and combines that data to create a pool of common coordinates. This way, if the hand “touches” the area where the texture is supposed to exist, the software calculates which areas of the user’s palm intersect the texture and uses an ultrasound haptics focal point on the specified location.

Secondly, in this chapter *focal point speed*, *focal point direction*, *focal point number*, *focal point distance* and *inter-element spacing* are studied. Their examination is done without the form of a texture. Instead, the parameters are tested by collecting roughness scores from each parameter. This is done by using one focal point to animate movement or by the use of one or more focal points traversing in a specified manner, and static focal points.

This chapter describes two studies which investigate (1) the texture discrimination rates of realistic textures, and (2) the roughness mediating abilities of each ultrasound haptics parameter on its own. In the first study, a number of realistic textures are presented and are required to be recalled and discriminated against. The second study studies *focal point speed*, *direction*, *inter-element spacing*, *number of focal points* and *focal point distance* parameters. Finally, this chapter aims to answer the first and second research questions: **RQ1** (How does the Hand Traversal Speed of an ultrasound focal point improve the dis- crimination of realistic textured surfaces?), and **RQ2** (How do changes in speed, focal point number, movement direction, and inter-element spacing affect perceived roughness scores?).

3.1.1 Chapter Structure

Section 3.2 describes the design and experimental methodologies for the realistically textured surfaces and how parameters such as the Hand Traversal Frequency of a focal point and TA affect texture discrimination. Section 3.3 focuses on studying the parameters of focal point speed, *direction*, *inter-element spacing*, *number of focal points* and *focal point distance*. Each section explains the research aims of the study involved, the experimental methodology, the results of each study, a discussion of the results, a list of limitations and finally, a summary.

3.2 Study 1: Hand Traversal Frequency and Tactile Acuity of a focal point

3.2.1 Research Aims

The study presented in this section introduces ultrasound haptic feedback by using a focal point that traverses a series of coordinates in the three-dimensional space that map into a realistic textured surface. The study's first aim is to determine whether the frequency with which a focal point traverses over a palm affects the discrimination between textured surfaces. I.e. measuring whether increasing or decreasing the frequency of a focal point helps participants produce better discriminatory results.

Another aim was to identify whether better TA allows a better discrimination rate over textured surfaces. Participants can have different TAs when using ultrasound haptics compared to typical contact material. The role of high TA in texture discrimination and texture composition is studied.

The aim of this study is to rank discrimination rates for different textured surfaces. This ranking will enable further study of these surfaces in a multimodal setting to assess the impact of additional modalities on discrimination rates.

The three main aims of this experiment are to:

1. determine whether the Hand Traversal Frequency of a focal point improves texture discrimination,
2. identify whether Tactile Acuity plays a role while discriminating ultrasound-generated textures, and
3. analyse which textured surfaces participants can discriminate seamlessly.

The objectives are to address the first research question (RQ1) and second research question (RQ2), as well as establish a set of textures for future studies into RQ4.

3.2.2 Methodology

Feedback Design

The generation of a textured surface is composed of three main phases: a) the continuous check of a user's hand position, b) The identification of the coordinates of the hand (palm and fingers) and the calculation or filtering of the coordinates that need haptic feedback and last c) produce haptic feedback based on preset values.

The identification of the user's hand and finger position is done by using a Leap Motion sensor. The Leap Motion sensor is able to provide relative location coordinates for the palm, fingers and bones of the hand. The UHEV1 (figure 3.1) has pre-installed a Leap Motion sensor.

As soon as a hand enters the view area of the Leap Motion sensor, the system calculates all of the coordinates and intersects them with a mathematical solution and/or a range of limits. The mathematical formulas and combinations of limits are called Plane Types (PT) since the different formulas can be seen as planes with varied textures. As soon as the hand coordinates intersect a PT, the tactile feedback points must be calculated. The system ensures that multiple feedback points are generated for every bone - typically 5 points per bone - and then creates a pool of randomly ordered feedback points which are then filtered in such a way as to limit the number of coordinates that the system will produce ultrasound haptic feedback on. The number of feedback points left is based on the amount of time it has available to produce those feedback points, which is based on the HTF.

Using the aforementioned pool of semi-random coordinates, the system sequentially produces haptic feedback at every point based on the set HTF. HTF is an integer measured in Hertz describing how many feedback points are produced within a second, e.g. a 64Hz HTF means that 64 points have been processed within a second. Additional variables can be specified to manipulate a texture, such as the Wave Type that can be produced by the transducers, the Square Size (the area that a UGT can be produced) and the Wave Frequency. The system recalculates the hand position once the last feedback point has been registered.

Apparatus

Figure 3.1: An array of Transducers named Ultrahaptics Evaluation Kit 1 - Dragonfly (UHEV1)

In this experiment and the rest of the thesis, the studies will be performed using the UHEV1 array of transducers. This array allows the manipulation of its surrounding acoustic field by using its 16x16 (total 256) array of transducers. Each transducer is circular in shape, has a diameter of $\approx$ 1cm, has a 10.47 transducer pitch, and its frequency is at 40 kHz. UHEV1 can produce a total of 8 focal points simultaneously by using either the Amplitude Modulation or Time Point Streaming methodology. Additionally, UHEV1 is capable of all types of signal modulation with a 16000Hz maximum update rate.

Measures

This experiment has two independent variables: Hand Traversal Frequency and Textured Surface Type. Hand Traversal Frequency has two levels: 40Hz and 64Hz. The Textured Surface Type has four levels: Checker-board, Knurl, Sinusoid and Flat. There are two dependent variables: textured surface discrimination rate and haptic acuity.

Textured Surfaces

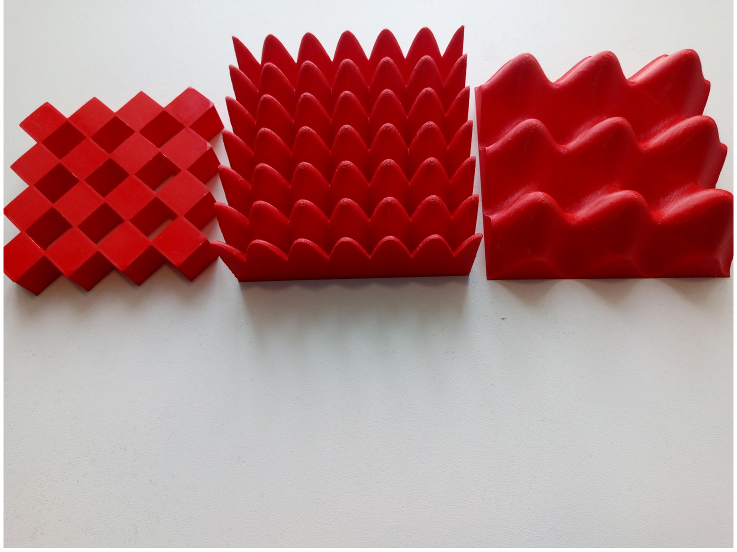


Figure 3.2: Visualisation using 3D printing of three out of four textured surfaces: Checkerboard, Knurl and Sinusoid.

The four textured surfaces, named Checkerboard, Knurl, Sinusoid, and Flat, are depicted in Figure 3.2 as 3D printed objects. The Flat surface is not included as it is a simple flat surface. Each textured surface measures 16x16 cm in two dimensions and 6cm in height. Due to the inability to accurately measure whether the haptic feedback is at the exact location on the palm, the values mentioned above are approximations. Although the software and equipment are designed to produce feedback in the correct location, it is possible that mechanoreceptors next to the specific area may be triggered instead, making the textured surfaces appear larger or smaller than their actual size.

The Flat textured surface is an entirely flat texture. The area at which the hand feels tactile feedback is between the 16x16 area and the height of 6cm. It can be imagined as a rectangular prism at which, if the hand intersects it, the hand feels constant, static tactile feedback.

The Checkerboard textured surface is created by interchangeably creating small areas of tactile feedback and areas without tactile feedback. The small areas are 2x2cm with the default height.

The Knurl textured surface uses a function to generate itself, which is restricted at the default height. The PT is equivalent to a plane composed of a sequence of pyramids. The function is $f(x,y) = (|mod(x,\alpha) - 2| + |mod(y,\alpha) - 2|) \cdot \frac{3}{2} + \beta$, where α is the tessellation width, and β is the displacement of the height in cm from the bottom of the plane.

Last, the Sinusoid textured surface is created by following the sinusoid function. The function is $f(x,y) = 3 \cdot \cos\left(\frac{\pi}{2} \cdot x\right) + \beta$, where β is the displacement of the height in cm from the bottom of the plane.

Hypotheses

- **H1** Texture discrimination will increase when the Hand Traversal Frequency (HTF) is increased because higher HTF will have a greater influence on secondary texture-defining parameters.
- **H2** Texture discrimination will improve when rougher textures are presented due to rougher surfaces providing more distinct tactile cues.
- **H3** Higher texture discrimination will be detected when participants with higher Tactile Acuity (TA) are tested because higher tactile acuity should allow the perception of finer structural texture details.

H1 asserts that increasing HTF when generating textured surfaces will enhance the rate at which participants can discriminate between textures. This hypothesis is based on the mechanism that higher HTF indirectly influences spatial parameters such as groove width or inter-element spacing, affecting texture perception. To test this, textured surfaces will be generated with varying levels of HTF, and participants will be tasked with distinguishing between these surfaces. It is expected that higher HTF will lead to increased texture discrimination rates, providing actionable insights into how HTF can be utilized to improve texture perception in various applications.

H2 suggests that participants will more easily discriminate rougher textured surfaces compared to smoother surfaces. This hypothesis is grounded in the principle that rough textures provide more distinctive tactile cues, which are critical for haptic perception. By controlling for other factors such as compliance, weight, and temperature, the study aims to isolate the effect of texture roughness on discrimination ability. Participants will be presented with a range of surfaces varying in roughness and will be tasked with identifying and discriminating between these surfaces based solely on texture. It is expected that rougher textures will result in higher discrimination rates, suggesting that texture roughness is a key factor in haptic perception.

H3 states that participants with higher TA will exhibit better rates of discriminating between different textured surfaces. Tactile acuity, defined as the ability to discern small structural details through touch, is predicted to correlate positively with texture discrimination performance. To test this hypothesis, participants' TA will be measured using standardized tests, and their performance in discriminating between different textured surfaces will be evaluated. The expected outcome is a positive correlation between TA and texture discrimination rates, indicating that higher TA significantly enhances an individual's ability to perceive and differentiate textures.

Hypotheses Testing

To test **H1** this study will consider HTF as a binary predictor for a successful discrimination rate. This means confusion matrices can be generated to understand the predictive capabilities of each level of HTF. Since this is a repeated measures study, where all participants are exposed to all IVs, a MacNemar test can be used to verify statistical significance.

H2 will be tested similarly to H1, making sure to compare the values between Flat and Checkerboard (the two smooth textured surfaces), with those of Knurl and Sinusoid (rough textured surfaces).

H3 will be tested by first identifying the mean HA of the participants, tag them into two groups, High Haptic Acuity (HHA) and Low Haptic Acuity (LHA). We can then use the HHA and LHA tags as predictors for correct texture discrimination. Confusion matrices can help understand their capabilities and a MacNemar's test will ensure statistical significance.

Procedure

The experiment is divided into three stages: a) the Two-point discrimination stage (2PD), b) the Exploration stage and c) the Texture identification stage. When the three stages are completed, every participant is required to answer a questionnaire. The three stages are presented visually using a flowchart in figure 3.3.

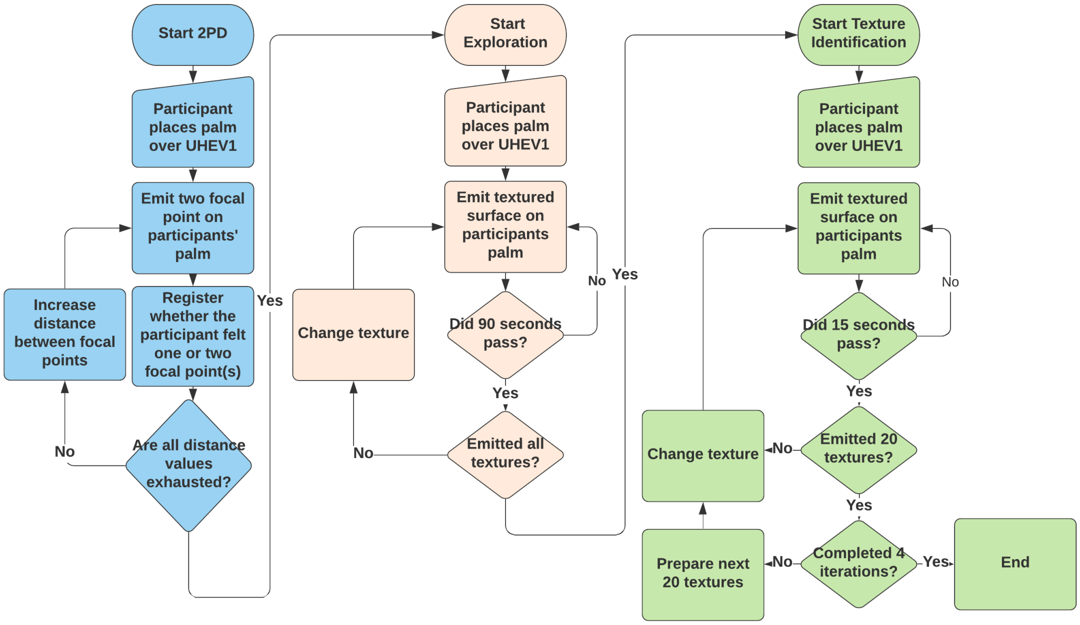


Figure 3.3: Event flow diagram of the procedure of study 1. The flowchart shows all three stages of the study.

Two-point discrimination. The aim of this stage is to measure the minimal distance that a participant can detect two unique points of haptic feedback and use that value during analysis to identify whether a lower distance affects the haptic perception or identification of a textured surface, i.e. if a participant can distinguish two points in small distances then he should be able to have superior texture discrimination. In order to collect the minimal displacement measure, an adjusted two-point discrimination (2PD) test is used. In general, a 2PD test focuses on testing a participant's ability to discriminate between single and double-point stimuli (each point typically having a 0.5mm diameter). A 2PD test usually starts off by having two haptic actuators next to each other on the skin of a participant in a way as such to create a single point of haptic feedback. The actuators' positions are continuously displaced in such a way as to increase their distance by a small margin, typically by a single millimetre.

In this experiment, the displacement distance was increased instead of a single millimetre to 2mm, 4mm, 6mm, 8mm, 10mm, 20mm, and 30mm. The reason for this difference was due to the low resolution of acoustic, haptic feedback on the palm. The structure of the experiment follows one iteration from which the user places their palm on top of UHEV1 and is emitted (in sequence from lowest to highest distance) two tactile feedback points. The user then is required to answer whether he discriminates against one or two tactile feedback points. The distance is always increased.

Exploration. The exploration stage introduces a participant to four textured surfaces, for which the participant is given 90 seconds to analyze and memorize. Every 90 seconds, i.e. when the user finishes memorizing a UGT, the user is given a paper where he is asked to note any distinguishing features that the mid-air texture may have had. It should be noted that participants were encouraged to adjust their previously written answers after every new mid-air texture, thus making connections between the different textures, e.g. texture A seemed rougher than texture B, or texture C felt to have spikes instead of curves. This stage introduces four unique mid-air textures, named A (Checkerboard), B (Flat), C (Knurl) and D (Sine), to every participant, which are generated using 64Hz HTF.

Texture identification. In this stage, the participants are tested to determine whether they can identify the textured surface from the exploration stage. The participants must complete four iterations of textured surface identifications, where every iteration consists of 20 randomly ordered textured surfaces. The participants are required to give an answer within 15 seconds. Throughout the experiment, the participants were required to wear headsets which outputted brown noise, thus reducing any external audible distractions (such as equipment noise). In addition to that, the users had to choose textures from a pool of eight different textures (four more than what they had explored in the Exploration Stage). The four additional textures are the 40Hz variants of the four original ones, and this was done to test whether HTF affects texture discrimination in any way.

Participants

Twenty participants enlisted for the study. The participants were composed of healthy young adults (aged 18-35) and primarily staff or students from the University of Glasgow. For each one-hour session, every participant has been paid £6 for full or partial completion of a study session.

3.2.3 Results

The results of this study are in the form of texture discrimination answers and questionnaire answers comprising nine-point Likert scale answers and text.

Effects of HTF

Two confusion matrices were generated to test the effects of HTF (one for 40Hz and one for 64Hz) and a subsequent MacNemar test was applied to ensure statistical significance. The confusion matrix for 64Hz HTF is shown in the table 3.1. Overall statistics produced from the confusion matrix are Accuracy=0.3488, 95% CI= (0.3157, 0.3829), No Information Rate=0.25, p-value[Acc > NIR]<0.05, Kappa=0.1317. Statistics by class are shown in table 3.2.

Table 3.1: Confusion Matrix HTF 64

Prediction	**Checkerboard**	**Flat**	**Knurl**	**Sinusoid**
Checkerboard	75	34	29	70
Flat	59	107	100	34
Knurl	37	44	52	51
Sinusoid	29	15	19	45

Table 3.2: Statistics by Class HTF 64

Metric	**Checkerboard**	**Flat**	**Knurl**	**Sinusoid**
Sensitivity	0.37500	0.5350	0.2600	0.22500
Specificity	0.77833	0.6783	0.7800	0.89500
Pos Pred Value	0.36058	0.3567	0.2826	0.41667
Neg Pred Value	0.78885	0.8140	0.7597	0.77601
Prevalence	0.25000	0.2500	0.2500	0.25000
Detection Rate	0.09375	0.1338	0.0650	0.05625
Detection Prevalence	0.26000	0.3750	0.2300	0.13500
Balanced Accuracy	0.57667	0.6067	0.5200	0.56000

The confusion matrix for 40Hz HTF is shown in the table 3.3. Overall statistics produced from the confusion matrix are Accuracy=0.3025, 95% CI= (0.2708, 0.3356), No Information Rate=0.25, p-value[Acc > NIR]<0.05, Kappa=0.07. Statistics by class are shown in table 3.4.

Table 3.3: Confusion Matrix for HTF 40

Prediction	**Checkerboard**	**Flat**	**Knurl**	**Sinusoid**
Checkerboard	42	43	36	72
Flat	19	36	41	12
Knurl	58	71	81	33
Sinusoid	81	50	42	83

Table 3.4: Statistics by Class for HTF 40

Metric	**Checkerboard**	**Flat**	**Knurl**	**Sinusoid**
Sensitivity	0.2100	0.1800	0.4050	0.4150
Specificity	0.7483	0.8800	0.7300	0.7117
Pos Pred Value	0.2176	0.3333	0.3333	0.3242
Neg Pred Value	0.7397	0.7630	0.7864	0.7849
Prevalence	0.2500	0.2500	0.2500	0.2500
Detection Rate	0.0525	0.0450	0.1013	0.1037
Detection Prevalence	0.2412	0.1350	0.3038	0.3200
Balanced Accuracy	0.4792	0.5300	0.5675	0.5633

Finally, a MacNemar test was employed to ensure statistical significance between the two HTF values. McNemar's test for HTF 64Hz and 40Hz shows a test statistic Chi-squared=101.29 with 1 degree of freedom and a p-value<0.05.

Effects of Textured Surfaces

To test the effects of textured surface design an overall confusion matrix will be presented and a MacNemar test will be employed for statistical significance. The overall confusion matrix is shown in the table 3.5. Overall statistics produced from the confusion matrix are Accuracy=0.3256, 95% CI= (0.3027, 0.3492), No Information Rate=0.25, p-value[Acc > NIR]<0.05, Kappa=0.1008. Statistics by class are shown in table 3.6.

Table 3.5: Overall Confusion Matrix

Prediction	**Checkerboard**	**Flat**	**Knurl**	**Sinusoid**
Checkerboard	117	77	65	142
Flat	78	143	141	46
Knurl	95	115	133	84
Sinusoid	110	65	61	128

Table 3.6: Overall Statistics by Class

Metric	**Checkerboard**	**Flat**	**Knurl**	**Sinusoid**
Sensitivity	0.29250	0.35750	0.33250	0.3200
Specificity	0.76333	0.77917	0.75500	0.8033
Pos Pred Value	0.29177	0.35049	0.31148	0.3516
Neg Pred Value	0.76397	0.78440	0.77238	0.7799
Prevalence	0.25000	0.25000	0.25000	0.2500
Detection Rate	0.07312	0.08937	0.08313	0.0800
Detection Prevalence	0.25062	0.25500	0.26687	0.2275
Balanced Accuracy	0.52792	0.56833	0.54375	0.5617

Finally, a MacNemar test was employed to ensure statistical significance between the rough and smooth textures. McNemar's test for rough and smooth textured surfaces shows a test statistic Chi-squared=37.242 with 1 degree of freedom and a p-value<0.05.

Effects of Haptic Acuity

Collected the data for all subjects in regards to Haptic Acuity which is shown in figure 3.4 as a histogram of the lowest haptic acuity scores. Then the data was structured to produce a list of the lowest haptic acuity scores per subject, that is the smallest value that the participant felt at two distinct points. From that, the mean value of 4.22 with sd=2.05 was calculated. We used the mean values of 4 to separate the data into two groups, the HHA group where the smallest value of feeling two distinct points is equal to or less than 4, and LHA in the rest.

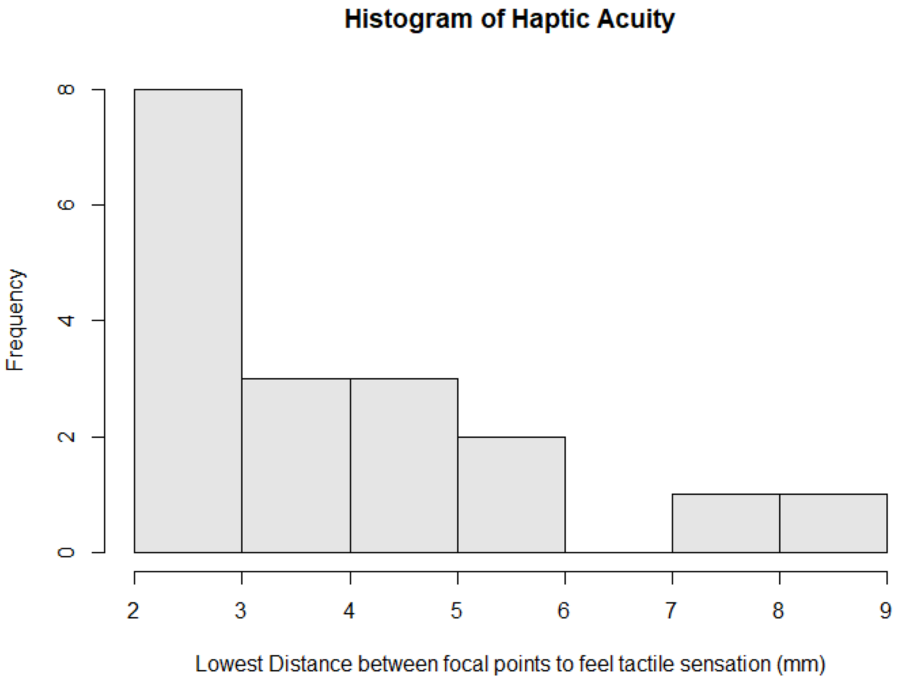


Figure 3.4: Histogram of Haptic Acuity

A confusion matrix for the HHA group was generated and shown in table 3.7. HHA statistics produced from the confusion matrix are Accuracy=0.3, 95% CI= (0.2623, 0.3398), No Information Rate=0.25, p-value[Acc > NIR]<0.05, Kappa=0.0667 and Mcnemar's Test p-Value>0.05. Statistics by class are shown in table 3.8.

Table 3.7: HHA Confusion Matrix

Prediction	**Checkerboard**	**Flat**	**Knurl**	**Sinusoid**
Checkerboard	41	27	26	52
Flat	28	47	38	19
Knurl	35	35	50	39
Sinusoid	36	31	26	30

Table 3.8: HHA Statistics by Class

Metric	**Checkerboard**	**Flat**	**Knurl**	**Sinusoid**
Sensitivity	0.29286	0.33571	0.35714	0.21429
Specificity	0.75000	0.79762	0.74048	0.77857
Pos Pred Value	0.28082	0.35606	0.31447	0.24390
Neg Pred Value	0.76087	0.78271	0.77556	0.74828
Prevalence	0.25000	0.25000	0.25000	0.25000
Detection Rate	0.07321	0.08393	0.08929	0.05357
Detection Prevalence	0.26071	0.23571	0.28393	0.21964
Balanced Accuracy	0.52143	0.56667	0.54881	0.49643

A confusion matrix for the LHA group was generated and shown in table 3.9. LHA statistics produced from the confusion matrix are Accuracy=0.3352, 95% CI= (0.3041, 0.3675), No Information Rate=0.25, p-value[Acc > NIR]<0.05, Kappa=0.1136 and Mcnemar's Test p-Value>0.05. Statistics by class are shown in table 3.10.

Table 3.9: LHA Confusion Matrix

Prediction	**Checkerboard**	**Flat**	**Knurl**	**Sinusoid**
Checkerboard	65	44	34	78
Flat	43	77	87	23
Knurl	51	70	71	37
Sinusoid	61	29	28	82

Table 3.10: LHA Statistics by Class

Metric	**Checkerboard**	**Flat**	**Knurl**	**Sinusoid**
Sensitivity	0.29545	0.3500	0.32273	0.37273
Specificity	0.76364	0.7682	0.76061	0.82121
Pos Pred Value	0.29412	0.3348	0.31004	0.41000
Neg Pred Value	0.76480	0.7800	0.77112	0.79706
Prevalence	0.25000	0.2500	0.25000	0.25000
Detection Rate	0.07386	0.0875	0.08068	0.09318
Detection Prevalence	0.25114	0.2614	0.26023	0.22727
Balanced Accuracy	0.52955	0.5591	0.54167	0.59697

Qualitative analysis

After the exploration stage, the participants were given a questionnaire to record their descriptions of the textures. From that questionnaire, A was mentioned 12 times as smooth, six times as rough and two times as fabric. Texture B was mentioned 13 times as smooth, four times as wind, four times as table and three times as flat. Texture C was mentioned seven times as flat and 3 times as smooth. Last, D was mentioned nine times as rough, four times as smooth, three times like wind and three times as curvy.

By the end of the identification stage, the participants were provided with a questionnaire containing 9-point Likert scale questions. The questions were: 1)"How difficult (0) or easy (8) was it to identify the textures?" 2) "How rough (0) or smooth (8) were the textures?" and 3)"How difficult (0) or easy (8) was it to complete the tasks?".

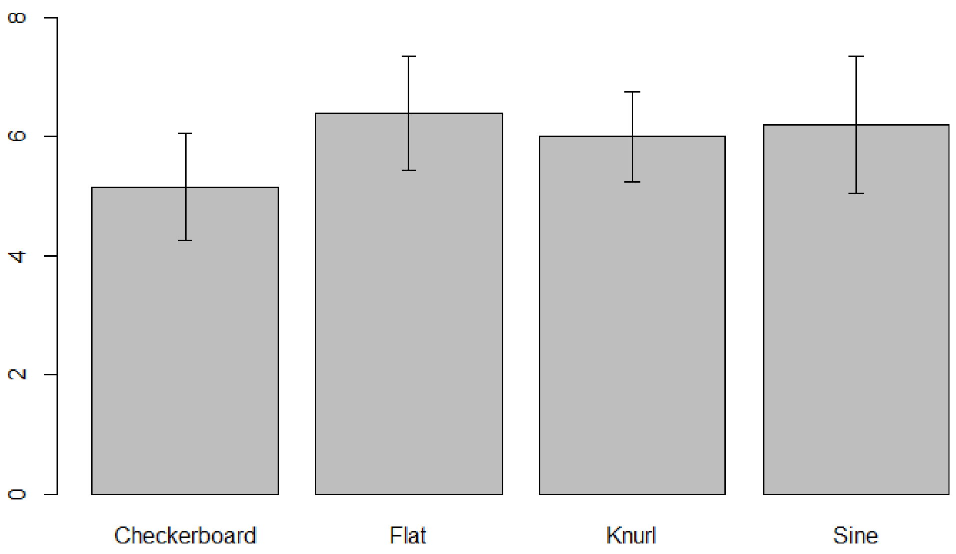


Figure 3.5: Barplot presents the participant's opinion on identifying each textured surface. The y-axis scores are 9-point Likert scale, with zero (0) representing difficulty in identifying and eight (8) as easy to identify. The x-axis are the textured surfaces names.

The first question collected the identification difficulty scores for each textured surface which produced the following means with their respective Confidence Intervals (CI): Checkerboard 5.15 (CI = 0.90), Flat 1.96 (CI = 0.96), Knurl 6.00 (CI = 0.75) and Sine 6.20 (CI = 1.15). The results mentioned above are shown in figure 3.5, where it is clear that participants considered all of the textured surfaces to be easy or almost easy to identify with no indication of the difference in difficulty between textures.

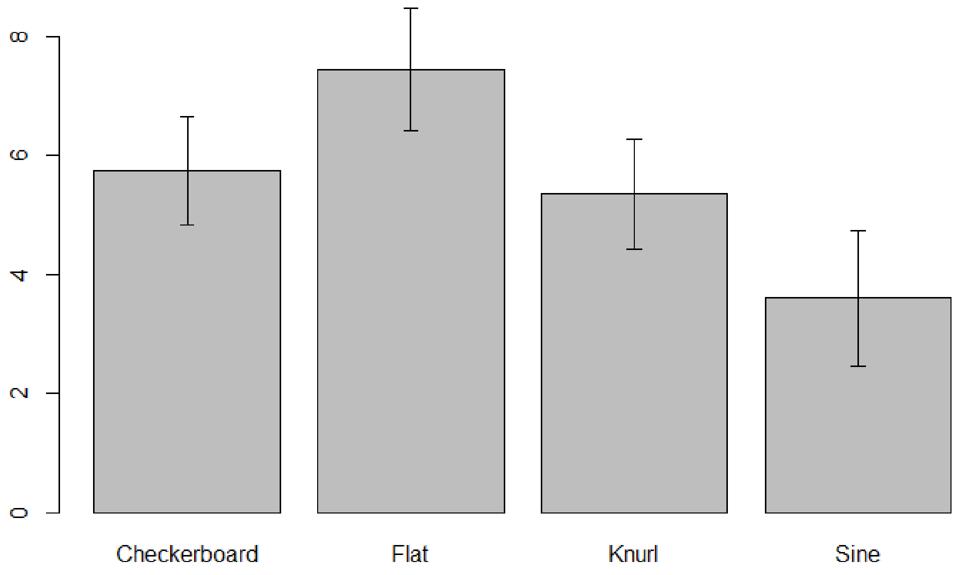


Figure 3.6: Barplot presents the participant's opinion on the roughness of each textured surface. The scores are 9-point Likert scale, with zero (0) representing a rough textured surface and eight (8) a smooth textured surface.

The second question collected the roughness scores for each textured surface which produced the following means with their respective CI: Checkerboard 5.75 (CI = 0.91), Flat 7.45 (CI = 1.03), Knurl 5.35 (CI = 0.92) and Sine 3.6 (CI = 1.13). The results mentioned above are shown in figure 3.6. The roughness scores between the Flat, Knurl and Sine textured surfaces are distinguished. The Flat is the smoothest, the Knurl is slightly rougher, and Sine is the roughest. The checkerboard value and confidence interval overlap; most of the values have no significant difference in roughness than the rest.

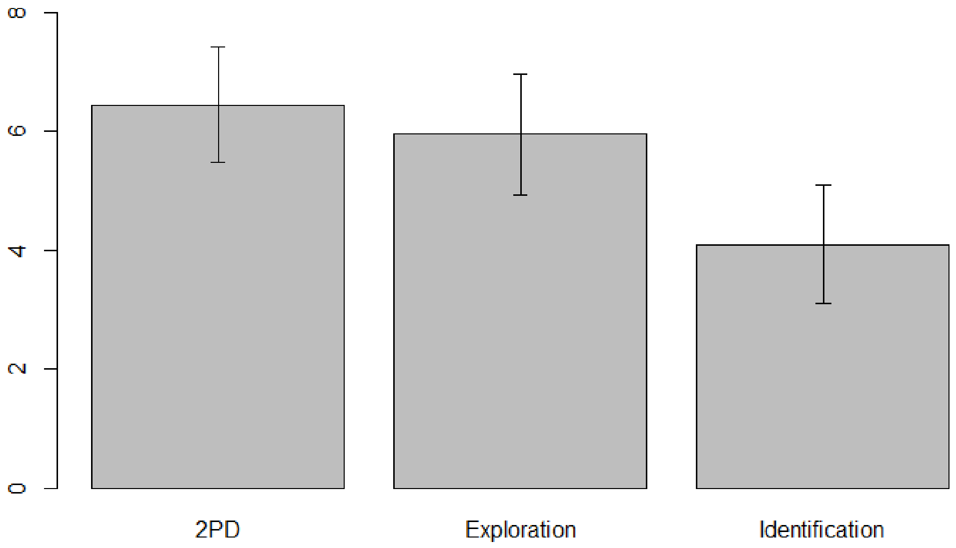


Figure 3.7: Barplot presents the participant's opinion on the difficulty of each stage in the study. The scores are 9-point Likert scale with zero (0) representing that a stage was difficult to complete and eight (8) a stage was easy to complete.

The third question collected the difficulty scores for each stage in the study. The mean scores and their respective CI values of this question are 2PD 6.45 (CI = 0.98), Exploration 5.95 (CI = 1.02) and Identification 4.10 (CI = 0.99). The results are visualised in figure 3.7, which shows that the Identification stage was significantly harder to complete than the 2PD stage.

3.2.4 Discussion

Study 1 was an initial investigation of the effects of HTF and HA on texture discrimination of textured surfaces. In this study, a participant could perceive four different textured surfaces at two HTF values, totalling eight unique tactile sensations via ultrasound haptics. The results have shown that increased HTF can increase discrimination rates for Checkerboard and Flat textured surfaces but reduced discrimination rates on Knurl textured surfaces and negligible change on the Sine surface.

> **H1** Texture discrimination will increase when the Hand Traversal Frequency (HTF) is increased because higher HTF will have a greater influence on secondary texture-defining parameters.

The **H1** hypothesis received mixed results. The results show that even though HTF is statistically significant for modulating textured surfaces' discrimination rate, it affects each textured surface differently or at all. By examining each texture on its own and comparing the discrimination results with their apparent roughness, it can be hypothesized that smoother textured surfaces (such as Checkerboard and Flat) are complimented by the faster HTF. However, given the results' proximity to 50%, it should be noted that this can still be a matter of chance.

> **H2** Texture discrimination will improve when rougher textures are presented due to rougher surfaces providing more distinct tactile cues.

This hypothesis was based on the assumption that intense sensations, such as the feeling of a rough texture should be more apparent than smoother ones. However, the results show that Flat and Sinusoid had greater balanced accuracy. Even with the MacNemar test showing that the results are statistically significant, the balanced accuracies are too close to the 50% mean and the overall accuracy is too low to use texture as a predictor.

> **H3** Higher texture discrimination will be detected when participants with higher Tactile Acuity (TA) are tested because higher tactile acuity should allow the perception of finer structural texture details.

H3 has been disproven with this study's results. The HHA group has shown decreased discrimination scores overall. The overall results have not been found statistically significant. Even with balanced accuracies ranging within the 50% range essentially means a random chance of Haptic Acuity predicting the discrimination outcome.

3.2.5 Limitations

Study completion difficulty is a limitation. Figure 3.7 shows that participants thought the Identification stage was difficult, and the reason is multi-factored. Firstly, the identification stage, even with frequent breaks, strained the participants mentally and physically. For each identification stage iteration, the participants had to hover their right palms above the machine for some minutes. Multiple times, they used their other hand to help keep them stable. This is something that is resolved in future studies by using a stand for the arm to rest upon and splitting the studies into smaller iterations.

The mental strain was due to participants feeling difficulty in recognising the textured surfaces by the last two Identification iterations. The difficulty is due to participants having limited time to explore the textured surfaces in the Exploration stage and to the UHEV1 heating up, which consequently can change the perception of the textured surfaces. This limitation is again resolved in the rest of the studies in this thesis by adding longer pauses for equipment cooling and mental fatigue, on-demand pauses for mental fatigue and the choice for a longer exploration time for a better-textured surface recall.

Lastly, as mentioned in the discussion section, it is unknown how HTF affects each surface, which identifies a limitation of this study's more in-depth analysis of how participants felt the surfaces. Understanding how a participant perceives a surface and what unique features are used for discrimination is vital. Therefore, it is essential that future studies take actions that will record the participants' mindset and document their techniques. Such actions could require incorporating pre-study and post-study interviews, followed by thematic analysis, to identify patterns and themes that can emerge from the researcher's notes.

3.2.6 Summary

The three aims of the studies were to: (1) determine whether the speed that a focal point traverses over a palm can affect the discrimination between varying textured surfaces; (2) identify whether better TA allows a better discrimination rate over textured surfaces; and (3) rank the discrimination rate of the textured surfaces. These aims began to contribute an answer to the first research question of this thesis:

> **RQ1:** How do ultrasound haptics improve the discrimination of realistic tactile models with varying roughness structures?

In the previously mentioned hypothesis, we reject the first hypothesis, even though the results are statistically significant, the differences between the predictive capabilities are not great enough to confidently answer that hypothesis. Each textured surface seemed to be affected differently based on some unknown criteria. The second hypothesis has also been rejected since the balanced accuracies are too close to random chance. The third hypothesis was also rejected due to insignificant results.

The study also revealed several areas for improvement. Future studies should allocate more time for users to fully memorize a textured surface, ensuring they can accurately recall and differentiate between textures. Additionally, it is important to provide longer breaks and pauses for participants, as recalling textured surfaces can cause mental strain and allowing the equipment to cool down between sessions is necessary. Implementing on-demand pauses will help participants manage mental fatigue more effectively. To prevent physical fatigue, the experimental design should include a handstand support. Finally, when creating new textured surfaces, the focus should be on transmitting specific, easily discriminated features rather than attempting to replicate realistic surfaces. This approach will enhance the clarity and effectiveness of texture discrimination in future studies.

3.3 Study 2: Examination of Isolated Ultrasound Haptic Parameters

3.3.1 Research Aims

Study 2 studies how, in isolation, some haptic parameters can produce rougher sensations by using ultrasound haptics. Four parameters will be studied: the *direction of motion*, the *number of focal points*, the *distance between focal points*, and finally, the *inter-element spacing* between focal points. The first aim is to analyze each parameter individually and measure its effectiveness in emitting a rough or smooth sensation. Identifying the roughness-mediating ability of every parameter can allow making future assumptions on producing more complex tactile sensations that can produce a specific roughness score.

The second aim is to conclude with an understanding of how participants score non-contextual tactile sensations from isolated parameters. By forcing each parameter to be actuated on its own, we can clearly study the thought process of each participant. The tactile sensations are designed to remain simplistic in design so a participant can extrapolate his thought process freely while grading a tactile sensation. Understanding the thought process between feeling and scoring roughness can inform future design choices regarding generating complex tactile sensations.

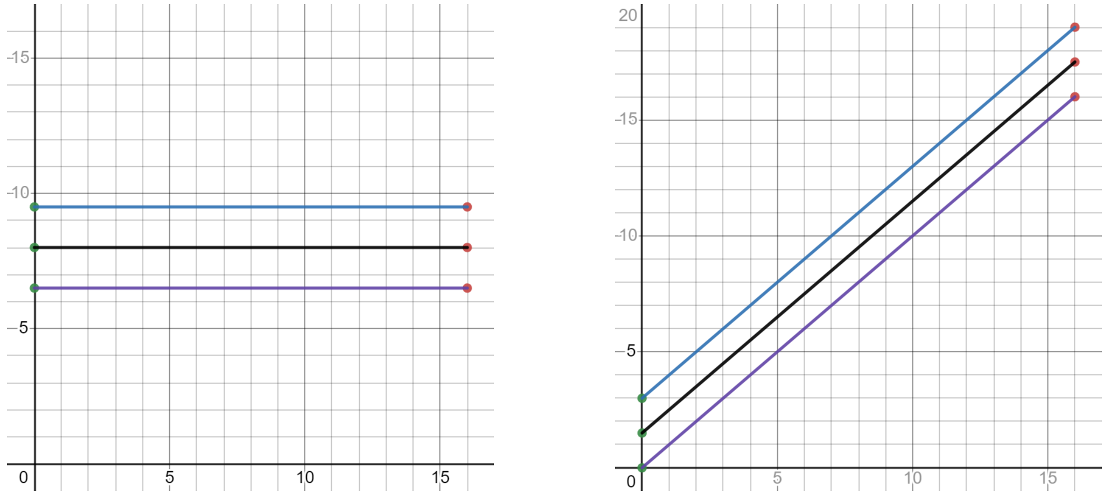
1. Analyze the roughness-mediating capabilities of each parameter on its own separately.
2. Examine how participants score roughness when actuated with non-contextual tactile sensations from isolated parameters.

These aims contribute an answer to the second research question (**RQ2**) of this thesis: How do changes in speed, focal point number, movement direction, and inter-element spacing affect perceived roughness scores?

3.3.2 Methodology

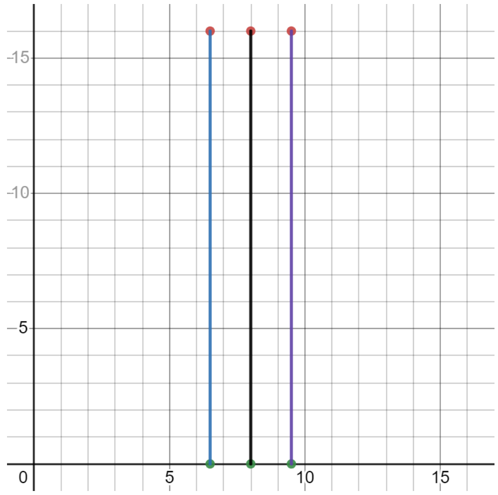
Feedback Design

Four designs are for consideration, the direction of motion, the number of focal points, the distance between focal points, and the inter-element spacing between focal points.



(a) Horizontal direction.

(b) Diagonal direction



(c) Vertical Direction

Figure 3.8: Graphs present the three different directions for the study. The green points indicate the start of the travel, and the red points indicate the end of the travel.

For direction, a single focal point was generated that can travel in three directions: vertically, horizontally, and diagonally. Given a 16x16 grid (see figure 3.8), the horizontal movement starts from (0, 6.5), (0, 8), and (0, 9.5), which travel horizontally to (16, 6.5), (16, 8), and (16, 9.5). The vertical movement starts from (6.5, 0), (8, 0), and (9.5, 0) and travels vertically to (6.5, 16), (8, 16), and (9.5, 16). Finally, the diagonal movement starts from (0, 0), (0, 1.5), and (0, 3) and travels diagonally to (16, 16), (16, 17.5), and (16, 19). The movement speed of the focal points is 7.32mm/s, and inter-element spacing is 2cm. Given the constant speed and great travel distance for the diagonal movement, the duration of the diagonal movement is longer by 1s. The movement repeats by jumping to the starting coordinates.

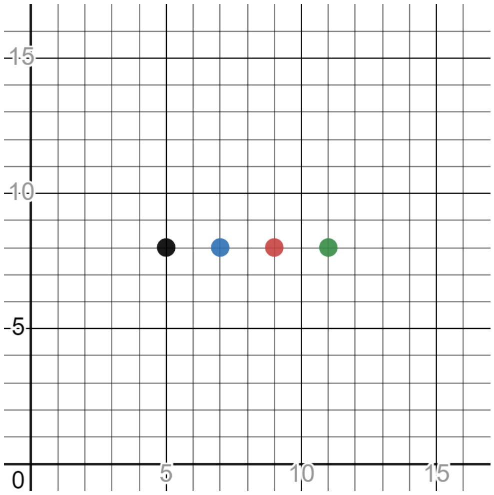
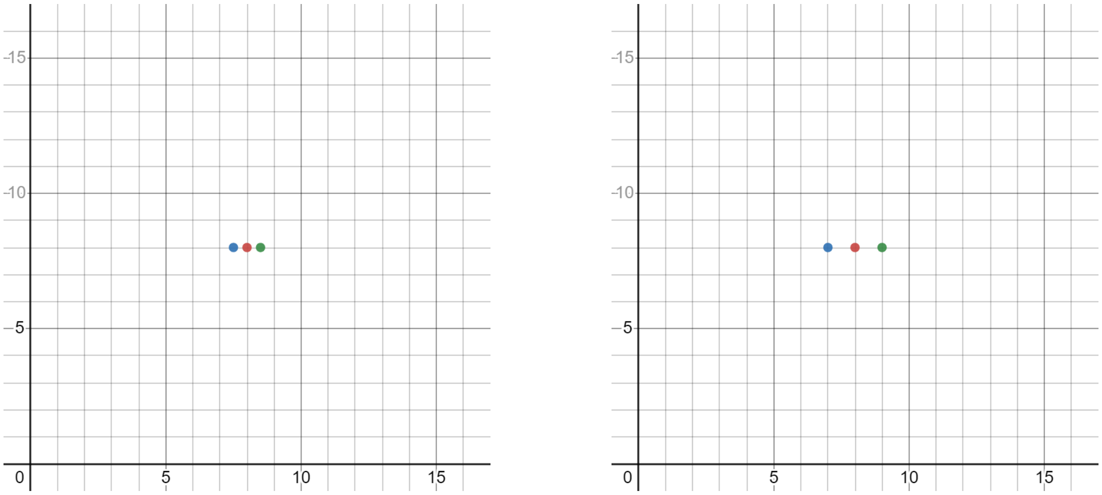
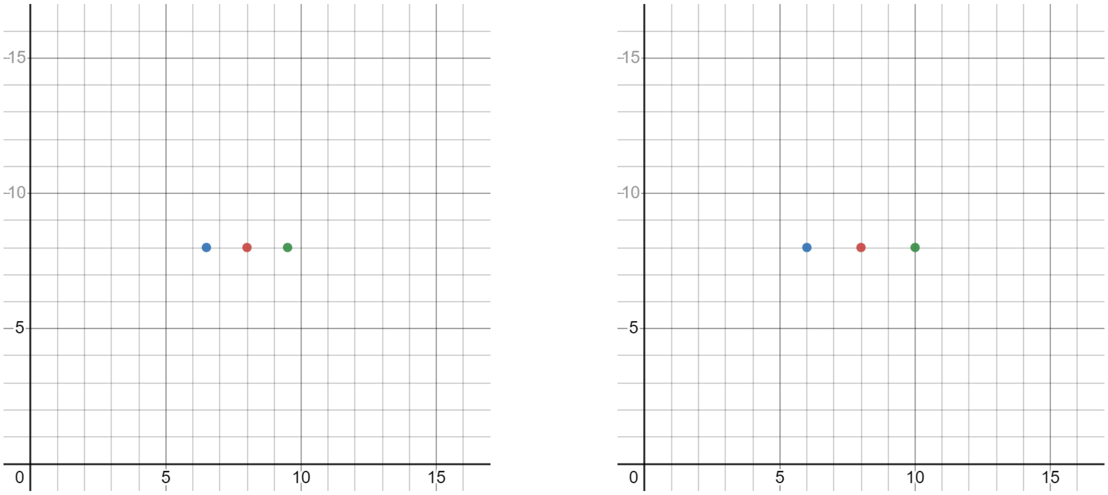


Figure 3.9: Graph showing the focal points when studying the number of focal points. The focal points in sequence of presentation are the red A=(9, 8), blue B=(7, 8), green C=(11, 8) and black D=(5, 8).

For studying the number of focal points, up to four static focal points were generated at maximum intensity. The focal points were centred in the middle of the palm (see figure 3.9). The four focal points have static loci within a 16x16 graph which are A=(9, 8), B=(7, 8), C=(11, 8) and D=(5, 8). When presenting the focal points, a number indicates how many are presented, and the presentation starts from coordinate A (the first focal point) and ends with D (the last). Therefore, if three focal points are needed, A, B and C will be presented.



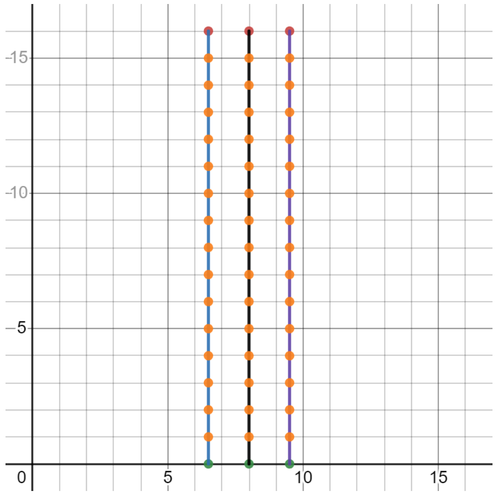
(a) 0.5cm (b) 1cm



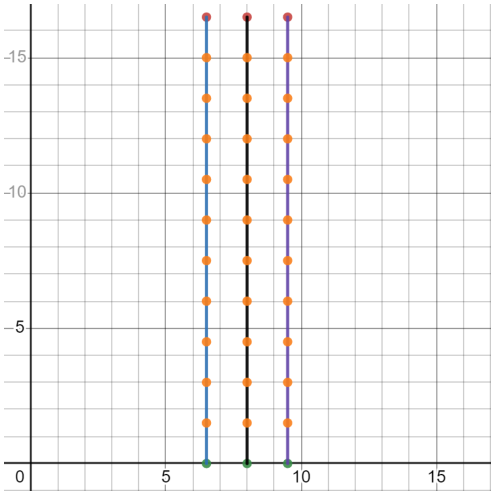
(c) 1.5cm (d) 2cm

Figure 3.10: Graphs presenting the four different distances for the focal points when studying the distance of focal points.

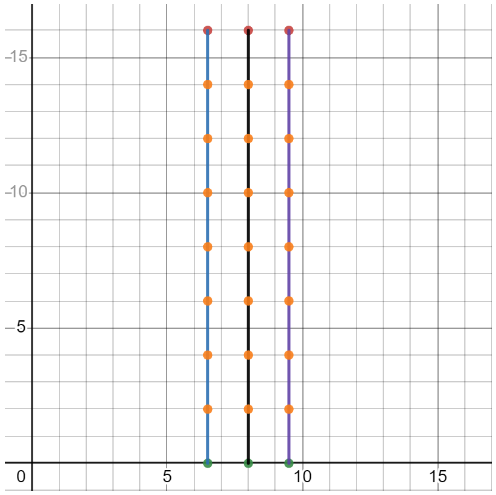
For studying the distance of focal points three static focal points were generated with the distance between them changing. Four distance values are available, 0.5cm, 1cm, 1.5cm, and 2cm. The three focal points are presented horizontally, with the first focal point being at (8,8) and the other two being a distance equal to the required distance to the left and the right. E.g. for distances equal to 1cm, the focal point coordinates are (7, 8), (8, 8) and (9, 8). Figure 3.10 visually represents the focal points at different distances.



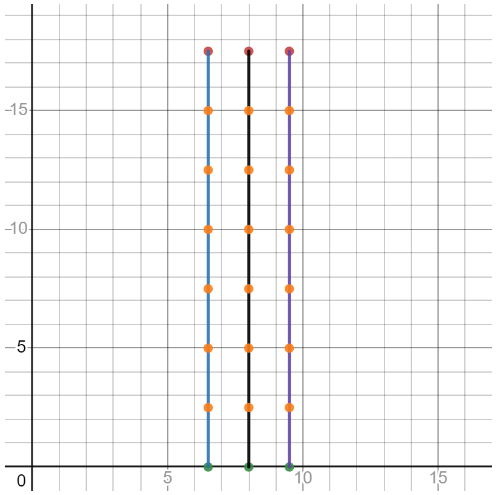
(a) 1cm



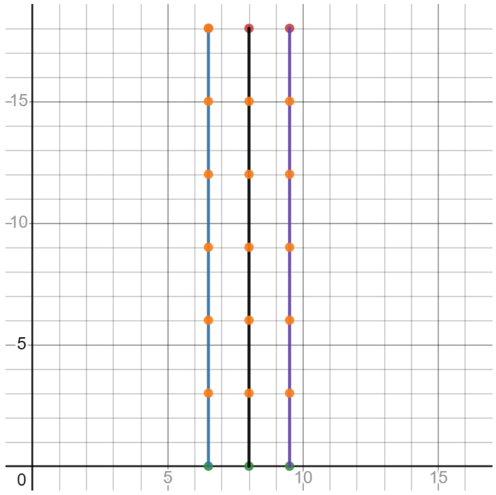
(b) 1.5cm



(c) 2cm



(d) 2.5cm



(e) 3cm

Figure 3.11: Graphs present the focal points' movement during the inter-element-spacing study. Green points indicate the start, and red ones indicate the end. The yellow points are the inter-element spacing between the green and red movements.

For studying the inter-element spacing, three animated focal points with the same speed moved in a vertical direction, but each hop's distance differed (see figure 3.11. E.g. a focal point moving from (8,0) to (8,16) with an inter-element spacing of 1cm would move to (8, 1), (8, 2) and so on, whereas the same focal point with an inter-element spacing of 2cm would move from (8,0) to (8, 2), (8, 4) and so on. The movement speed of the focal points is 7.32mm/s.

Lastly, the height of the handstand has been set to 12cm above the UHEV1 transducers, which also forces changes to the height parameter of the focal points. The height aims to improve the focal points' intensity since Study 1 has shown that some users had difficulty perceiving the focal points.

Measures

The experimental design for this study is comprised of five IVs which are: the movement speed of a focal point, the direction of movement, the number of focal points, the distance between focal points and inter-element spacing. The movement speed of a focal point has four values: 0mm/s, 20.5mm/s, 73.2mm/s and 207.3mm/s. The direction of movement has three values: vertical, right-diagonal and horizontal movement. The number of focal points has four levels: 1, 2, 3 and 4 simultaneous focal points. The distance between focal points has four values: 0.5cm, 1cm, 1.5cm and 2cm. Finally, the inter-element spacing has five values: 1cm, 1.5cm, 2cm, 2.5cm and 3cm.

The study has one DV: magnitude estimation of subjective roughness scores. The roughness scores are collected by presenting tactile sensations to a participant, who is then allowed to use a scale-free roughness score that signifies the relationship between tactile sensation and subjective roughness. These scores are then standardised so they can be quantitatively studied. There are two audio-recorded interviews, one at the beginning of a study session and one at the end of it.

Hypotheses

- **H1** Rougher sensations will be perceived if the direction of focal point movement is directed to more sensitive parts of the palm because that will enhance perceived tactile intensity.
- **H2** Subjective roughness perception will increase if the number of focal points increases because that will create the illusion of a macroscopic texture.
- **H3** Perceived roughness will increase if the distance between focal points is increased because it will increase the gap between elements.
- **H4** Subjective roughness will increase when the inter-element spacing of a moving focal point is increased because a greater area of the skin will be indented.

H1 hypothesizes that specific directions of motion of a focal point can emit a rougher sensation during haptic experiences. This hypothesis is based on the idea that different areas of the palm have varying sensitivity to tactile feedback [152]. By moving a focal point over more sensitive areas, such as the fingertips, the intensity of tactile feedback is expected to increase. Consequently, the direction of the focal point's movement, covering more sensitive areas, should modulate the perception of roughness.

H2 hypothesizes that an increasing number of focal points present during a haptic experience can increase the perceived subjective roughness. The hypothesis suggests that more focal points can create the illusion of a macroscopic texture, making the haptic sensation feel rougher. By simulating multiple focal points on the palm simultaneously, the texture should appear more realistic and emit a rougher sensation.

H3 hypothesizes that increasing the gap between focal points should promote rougher tactile sensations. The gap between the elements that constitute a surface is the most critical factor in affecting perceived roughness [34]; however, specific distance values are not explored. Therefore, this hypothesis assumes increasing the gap could increase participants' subjective roughness perception.

H4 assumes that when a focal point moves, the hop distance between one locus to another (i.e. inter-element spacing) is responsible for modulating the subjective roughness percept. Given each focal point's area of effect (1cm), in terms of skin indentation and tactile feedback, a greater inter-element spacing will actuate on a greater area and will indent more skin, causing increased perceived roughness. Therefore, this hypothesis expects that greater inter-element spacing should emit a rougher sensation to a participant.

Testing the Hypotheses

The experimental design of this study includes five independent variables (IVs) and one dependent variable (DV). The IVs are the movement speed of a focal point (quantitative continuous, four levels), the direction of movement (categorical nominal, three levels), the number of focal points (quantitative discrete, four levels), the distance between focal points (quantitative continuous, four levels), and the inter-element spacing (quantitative continuous, five levels). The DV is the magnitude estimation of subjective roughness scores (quantitative continuous), assessed by participants rating their perceived roughness of tactile sensations.

Datasets will be standardised on a 0 to 1 scale and normality will be tested using the Shapiro-Wilk test which is effective for small to medium-sized samples. If data is normal, a subsequent Leneve test will check the assumption of equal variances, which is crucial for the validity of ANOVA.

All hypotheses will be tested with a One-Way ANOVA (parametric) which tests the difference in means among three or more groups. In the case of non-normal dataset distribution, a Kruskal-Wallis test will be employed which compares the medians across groups. Kruskal-Wallis is a non-parametric alternative to ANOVA, used when the data does not meet ANOVA's assumptions. A post-hoc test is required after Kruskal-Wallis which will be a Nemenyi test.

Procedure

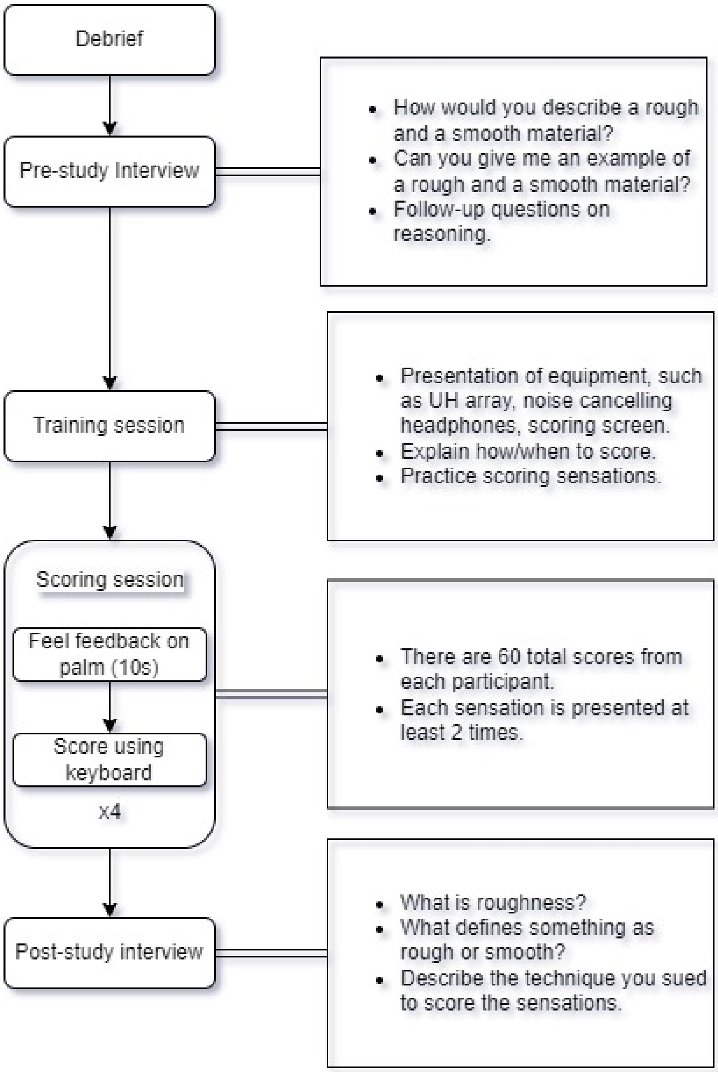


Figure 3.12: The figure presents the procedure each participant is required to attend in Study 2.

A single study session investigates all of the parameters mentioned earlier exclusively, i.e. in every study session. The participants will conduct five stages where every stage focuses on one of the variables. Figure 3.12 summarises the steps a participant takes during a study session. Initially, the researcher welcomes the participant in a controlled laboratory. The researcher asks the participant two questions that aim to bootstrap the participants' haptic vocabulary in regard to material roughness. The two questions are the following: "How would you describe a rough and a smooth material?" and "Can you give me an example of a rough and a smooth material?".

If the participant is unable to clearly define at least a single quality or parameter that can define a material's roughness, the researcher will build upon the questions by asking the participant to give an example of a smooth or rough material and then continue with the given answer with a follow-up question which queries the participant on what does he think is the reason that that material is rough or smooth. By pushing the participant to think in terms of material attributes, the participant is expected to try and use that knowledge to understand further what material roughness is and thus make clearer judgements on the perceived tactile sensations that he will be actuated.

Following that, the researcher debriefs the participant on what he has to do throughout the scoring stage. During the debrief, the participant has the chance to understand how the different sensations feel and how to score properly. The participant will place his right arm on a marked stand, and his palm will hang out of it, facing with the open palm downwards towards the UHEV1. In addition to that, the participant wears a noise-cancelling headset that plays brown noise. The brown noise helps the participant concentrate and mask the sounds that the UHEV1 emits. Then, the participant can see a computer screen on their left containing an empty input field and a confirm button. The researcher then starts the experiment, which instantly starts outputting some tactile sensations on the user's palm for 10 seconds. Throughout that time, the input field and confirm button are unable to accept any values. Doing so forces the user to focus on the tactile sensations. When the 10 seconds have passed, the user scores the perceived roughness of the sensation after receiving a prompt. The scoring is performed using the magnitude estimation methodology. This process is repeated multiple times in order to cover all values for the current parameter. When the participant scores all of the values for the stage, the participant takes a 30-second break. The participant repeats these processes for every parameter.

Finally, the user conducts an audio-recorded semi-structured interview which finalizes the participant's study session. The interview focused on questions regarding the participant's opinion about "What is roughness?", "What defines something as rough or smooth?" and the techniques the participant used to evaluate the tactile sensations' roughness.

Participants

Nineteen participants were enlisted for the study. The participants were composed of healthy young adults (aged 18-35) and primarily staff or students from the University of Glasgow. For each one-hour session, every participant has been paid £6 for full or partial completion of a study session.

3.3.3 Results

These results are based on 1140 roughness scores (magnitude estimations) from 19 participants. The roughness scores for each parameter were analysed using RStudio. The datasets were first standardized so they could be properly analysed.

Effects of focal point speed

A dataset for the focal point speed has been collected, depicted visually in table 3.11.

Speed	**Mean**	**Median**	**SD**	**IQR**	**Min**	**Max**
0	-0.624	-0.692	0.894	1.02	-2.19	1.54
2.05	0.0384	-0.0877	1.31	2.12	-2.73	3.02
7.32	0.468	0.315	0.997	1.26	-1.94	3.70
20.73	0.458	0.466	0.932	1.16	-1.48	3.13

Table 3.11: Descriptive statistics for roughness scores across different speeds.

A Shapiro-Wilk normality test was conducted to assess whether the magnitude estimation of subjective roughness scores in the dataset follows a normal distribution. The results indicated that the data did not significantly deviate from normality (W = 0.99371, p = 0.4531). Since the p-value was well above the conventional threshold of 0.05, we fail to reject the null hypothesis of normality. Levene's Test for Homogeneity of Variance was conducted to assess the variances of the subjective roughness scores. The results of Levene's Test indicated a significant difference in variances across the groups, with an F value of 5.7898 and a p-value of 0.0007896. Specifically, the degrees of freedom for the speed variable were 3, and the residual degrees of freedom were 224. The highly significant p-value ($p < 0.001$) strongly rejects the null hypothesis of equal variances. The results a visualised in figure 3.13. These findings suggest that the assumption of homogeneity of variances is violated. Therefore, statistical analysis continues with the non-parametric Kruskal-Wallis test.

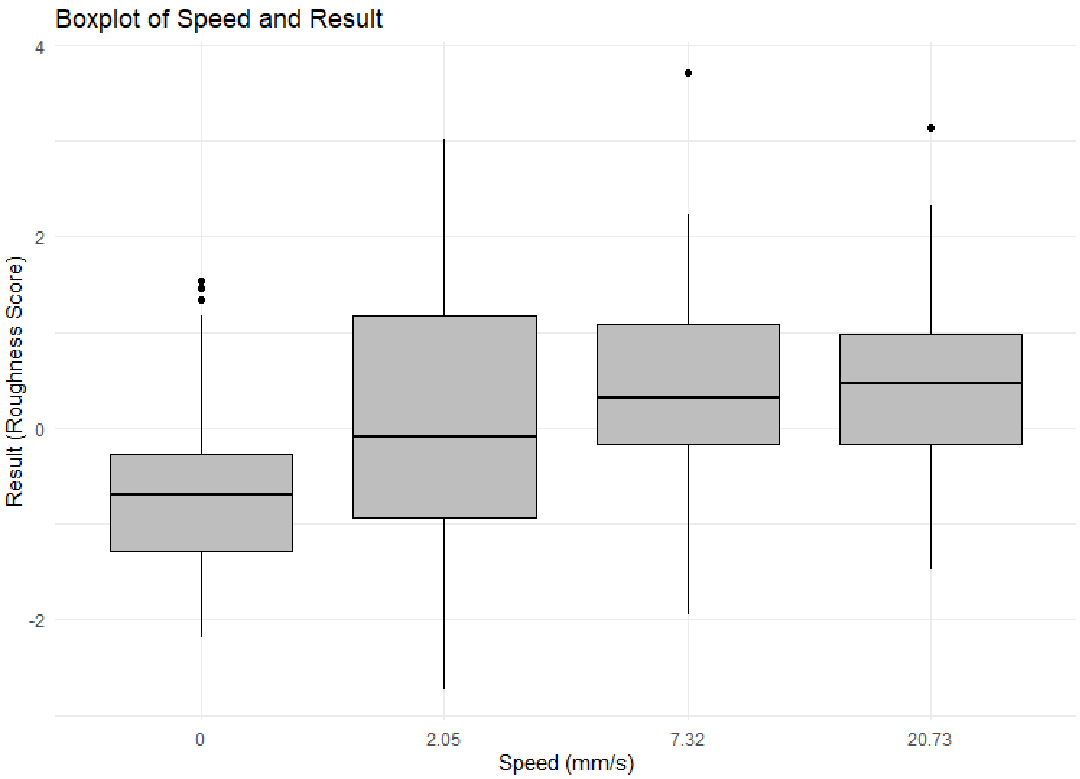


Figure 3.13: Boxplot of Speed and Result. The plot shows the distribution of subjective roughness scores across different movement speeds.

A Kruskal-Wallis rank sum test was conducted to evaluate the differences in subjective roughness scores across different levels of focal point speed. The results of the Kruskal-Wallis test indicated a statistically significant difference in roughness scores between the speed groups, chi-squared = 38.438 with 3 degrees of freedom, $p < 0.001$. These results suggest that at least one of the speed groups has a different distribution of roughness scores compared to the others. To understand the pairwise differences in the results a post-hoc Nemenyi test was employed.

A post-hoc Nemenyi test was employed for pairwise comparison. The family-wise error rate was controlled using an overall alpha level of 0.05. The results are based on the default Tukey distribution. The Nemenyi test revealed significant differences between several pairs of speed groups. The results indicated that the mean rank difference between 2.05 mm/s and 0 mm/s was significant (mean rank difference = 42.4649123, $p = 0.0033$), as was the difference between 7.32 mm/s and 0 mm/s (mean rank difference = 66.0877193, $p < 0.001$), and between 20.73 mm/s and 0 mm/s (mean rank difference = 66.5350877, $p < 0.001$). No significant differences were found between the other pairs. Results can be seen in table 3.12.

Comparison	Mean Rank Difference	p-value	Significance
2.05 - 0	42.4649123	0.0033	**
7.32 - 0	66.0877193	5.3e-07	***
20.73 - 0	66.5350877	4.3e-07	***
7.32 - 2.05	23.6228070	0.2229	
20.73 - 2.05	24.0701754	0.2081	
20.73 - 7.32	0.4473684	1.0000	

Table 3.12: Results of Nemenyi post hoc test for pairwise comparisons between speed groups.

Effects of number of focal points

A dataset for the number of focal points has been collected, depicted visually in table 3.13.

Directivity	Mean	Median	SD	IQR	Min	Max
Horizontal	0.442	0.349	1.19	1.31	-2.31	3.66
Right Diagonal	0.554	0.610	0.961	1.58	-1.94	2.31
Vertical	0.313	0.349	0.837	1.28	-1.40	2.62

Table 3.13: Descriptive statistics for roughness scores across different focal point directions.

The results of the Shapiro-Wilk normality test indicated that the data did not significantly deviate from normality, W = 0.99113, p = 0.3755. Given that the p-value is greater than the conventional threshold of 0.05, we fail to reject the null hypothesis of normality. Therefore, it can be concluded that the roughness scores are approximately normally distributed for the different directions of movement. The Levene test results indicated that the variances are marginally unequal across the groups, with an F value of 2.701 and a p-value of 0.07007. Although the p-value is slightly above the conventional threshold of 0.05, it suggests that the assumption of equal variances is not strongly violated but is close to significance. Both parametric and non-parametric tests can be considered, however, a non-parametric test like Kruskal-Wallis seems most appropriate.

The results of the Kruskal-Wallis test indicated no statistically significant difference in roughness scores between the different directions of movement, chi-squared = 2.3184 with 2 degrees of freedom, p = 0.3137. Given that the p-value > 0.05, we fail to reject the null hypothesis. This suggests that there are no significant differences in roughness perception across the different directions of movement tested. A visual representation of the results is shown in figure 3.14.

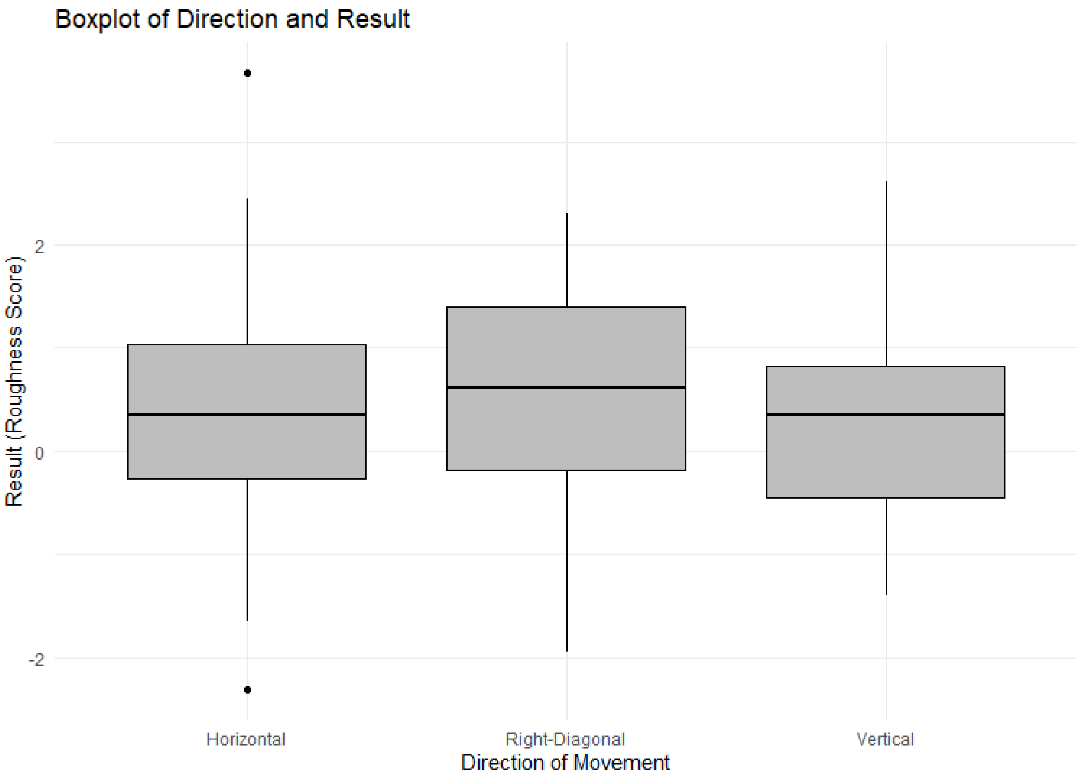


Figure 3.14: Boxplot of Direction and Result. The plot shows the distribution of subjective roughness scores across different directions.

Effects of quantity of focal points

A dataset for the number of focal points has been collected, depicted visually in table 3.14.

Quantity	Mean	Median	SD	IQR	Min	Max
1	-1.11	-1.02	0.583	0.688	-2.26	0.0668
2	-0.594	-0.574	0.610	0.525	-1.45	2.08
3	-0.762	-0.944	0.576	0.512	-1.53	1.17
4	-0.698	-0.832	0.633	0.605	-1.94	2.03

Table 3.14: Descriptive statistics for roughness scores across different quantities of focal points.

The results of the Shapiro-Wilk normality test indicated a significant deviation from normality, W = 0.93581, $p < 0.001$. Given that the p-value is significantly less than the conventional threshold of 0.05, we reject the null hypothesis of normality. Therefore, it can be concluded that the roughness scores are not normally distributed for the different quantities of focal points. Therefore a Kruskal-Wallis non-parametric test will be used to test statistical significance.

The results of the Kruskal-Wallis test indicated a statistically significant difference in roughness scores between the different quantities of focal points, chi-squared = 21.329 with 3 degrees of freedom, and $p < 0.001$. Given that the p-value is significantly less than the conventional threshold of 0.05, we reject the null hypothesis. This suggests that there are significant differences in roughness perception across the different quantities of focal points tested. Box plot showing the interquartile ranges of the different quantities can be seen in figure 3.15

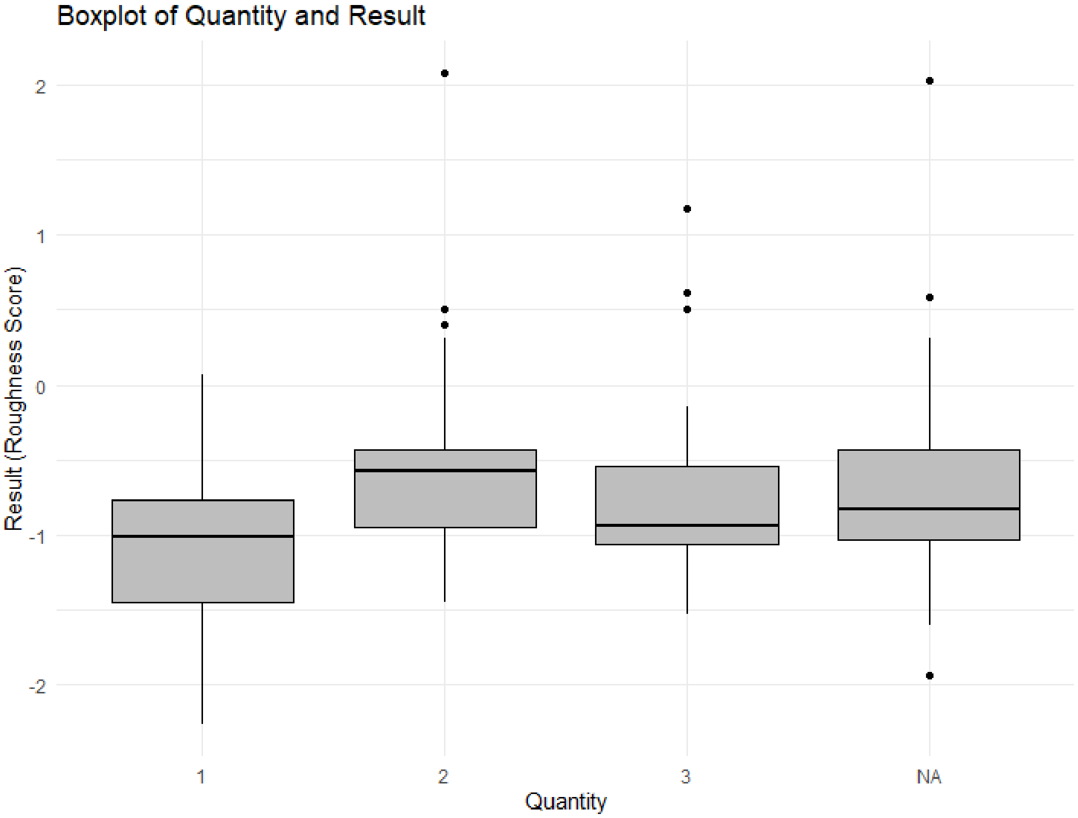


Figure 3.15: Boxplot of Direction and Result. The plot shows the distribution of subjective roughness scores across different focal point numbers.

A post-hoc Nemenyi test was employed for pairwise comparison. The family-wise error rate was controlled using an overall alpha level of 0.05. The results are based on the default Tukey distribution. The Nemenyi test results revealed several significant differences between groups. The pairwise comparisons indicated that the mean rank difference between 2 focal points and 1 focal point was significant (mean rank difference = 55.350877, $p < 0.001$). Similarly, the difference between 4 focal points and 1 focal point was also significant (mean rank difference = 39.631579, $p < 0.01$). There was a marginally significant difference between 3 focal points and 1 focal point (mean rank difference = 31.649123, $p = 0.0510$). Results are listed in table 3.15.

Comparison	Mean Rank Difference	p-value	Significance
2 - 1	55.350877	4.4e-05	***
3 - 1	31.649123	0.0510	.
4 - 1	39.631579	0.0073	**
3 - 2	-23.701754	0.2203	
4 - 2	-15.719298	0.5807	
4 - 3	7.982456	0.9170	

Table 3.15: Nemenyi post hoc test results for pairwise comparisons between quantities of focal points.
Notes: Significance codes: *** p < 0.001, ** p < 0.01, * p < 0.05, **.** p < 0.1, p >= 0.1

Effects of focal point distance

A dataset for the focal point distance has been collected, depicted visually in table 3.16.

Distance	Mean	Median	SD	IQR	Min	Max
0.5	-0.315	-0.374	0.579	0.590	-1.46	1.17
1	-0.390	-0.482	0.647	0.487	-1.50	2.03
1.5	-0.467	-0.548	0.611	0.739	-1.50	1.35
2	-0.419	-0.482	0.596	0.739	-1.46	1.17

Table 3.16: Descriptive statistics for roughness scores across different distances between focal points.

A Shapiro-Wilk normality test was conducted to assess the distribution of subjective roughness scores for different distances. The results indicated a significant deviation from normality, W=0.93064, p<0.001. Given that the p-value is significantly less than the conventional threshold of 0.05, we reject the null hypothesis of normality. Therefore, it can be concluded that the roughness scores are not normally distributed for the different distances between focal points. Therefore a Kruskal-Wallis non-parametric test will be used to test statistical significance.

The results of the Kruskal-Wallis test indicated no statistically significant differences in roughness scores between the different distances of focal points, chi-squared = 3.2723 with 3 degrees of freedom, p = 0.3515. Given that the p-value is greater than 0.05, we fail to reject the null hypothesis. This suggests that there are no significant differences in roughness perception across the different distances of focal points tested. Boxplot results are shown in figure 3.16.

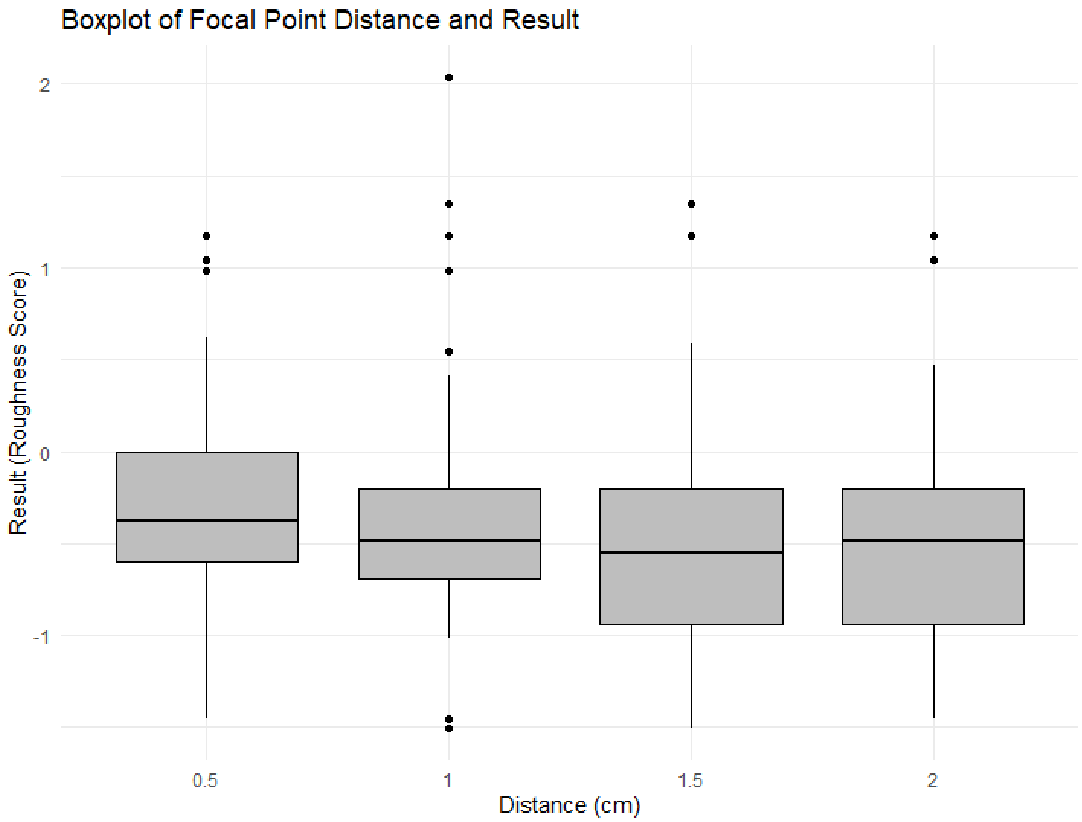


Figure 3.16: Boxplot of Focal Point Distance and Result. The plot shows the distribution of subjective roughness scores across different focal point distances.

Effects of inter-element spacing

A dataset for the element spacing has been collected, depicted visually in table 3.17.

Element Spacing	Mean	Median	SD	IQR	Min	Max
1	0.633	0.654	0.761	0.917	-1.11	2.18
1.5	0.913	0.981	0.709	1.03	-0.601	2.26
2	0.452	0.466	0.809	1.04	-1.60	2.18
2.5	0.573	0.566	0.812	1.15	-1.60	2.22
3	0.532	0.584	0.605	0.806	-0.586	1.70

Table 3.17: Descriptive statistics for roughness scores across different element spacings.

A Shapiro-Wilk normality test was conducted to assess whether the distribution of subjective roughness scores for different element spacings follows a normal distribution. The results indicated a significant deviation from normality, W=0.98886, p=0.02765. Given that the p-value is less than 0.05, we reject the null hypothesis of normality. Therefore, it can be concluded that the roughness scores are not normally distributed for the different element spacings. Therefore a Kruskal-Wallis non-parametric test will be used to test statistical significance.

The results of the Kruskal-Wallis test indicated a statistically significant difference in roughness scores between the different element spacings, chi-squared = 11.353 with 4 degrees of freedom, p = 0.02287. Given that the p-value is less than the conventional threshold of 0.05, we reject the null hypothesis. This suggests that there are significant differences in roughness perception across the different element spacings tested. Boxplot showing element spacing results in figure 3.17.

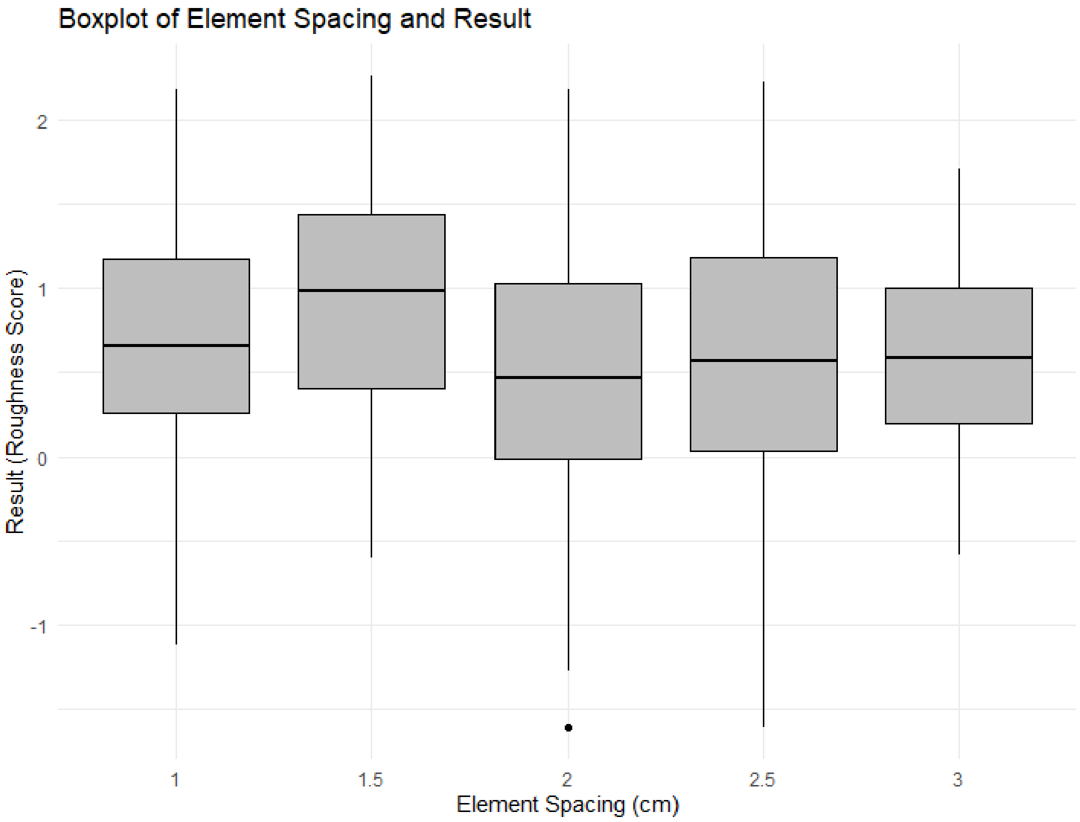


Figure 3.17: Boxplot of Element Spacing and Result. The plot shows the distribution of subjective roughness scores across different element spacing distances.

A post-hoc Nemenyi test was employed for pairwise comparison, shown in table 3.18. The family-wise error rate was controlled using an overall alpha level of 0.05. The results are based on the default Tukey distribution. the results show a difference between 2 and 1.5 element spacing, as well as the marginal significance between 3 and 1.5, suggesting some variability in roughness perception depending on the element spacing.

Comparison	Mean Rank Difference	p-value	Significance
1.5 - 1	25.666667	0.4573	
2 - 1	-21.657895	0.6258	
2.5 - 1	-9.043860	0.9772	
3 - 1	-14.921053	0.8702	
2 - 1.5	-47.324561	0.0185	*
2.5 - 1.5	-34.710526	0.1621	
3 - 1.5	-40.587719	0.0652	.
2.5 - 2	12.614035	0.9255	
3 - 2	6.736842	0.9925	
3 - 2.5	-5.877193	0.9956	

Table 3.18: Nemenyi post hoc test results for pairwise comparisons between element spacings. Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Thematic Analysis

The semi-structured interviews were transcribed, and a thematic analysis was conducted on those transcriptions. The analysis has noted 67 codes from the participants' results which were finally filtered down to the following three themes: “Apparent intensity”, “Frequency” and “Locality”.

Apparent intensity. Participants described a tactile sensation as rougher if they felt a *powerful* or *intense* sensation (P0, P4, P5, P6, P8, P9, P11, P12, P14). The intense sensations were expressed as “drilly” (P0), “needles” (P5), “prominent force” to the palm (P9), “jabbing” (P11), or “pointy” (P12). Our experimental design did not isolate intensity as a variable, although intensity varies with the number of points in each condition. A single point is more intense than multiple points emitted simultaneously, which decreases the amplitude of each point as the number of points increases. Previous literature does not indicate a clear relationship between intensity and roughness in a static model [34]. If such a relationship exists, our results show that it may differ when considering multiple points. As shown in Figure 3.15, the single, more intense point feels *smoother* than the multiple point conditions. The relationship between intensity and roughness implies that when users describe “intense” sensations, they perceive something independent from the objective intensity of the sensations emitted by the ultrasound array.

Frequency. A common theme was feeling repeating tapping on the palm. The participants described this as “pulsing” (P0, P9), “tapping” (P3, P14) or “frequency” (P6, P11). The participants described that feeling specific spots being “tapped” very fast resulted in rougher sensations. Additionally, P3 mentioned that if the tapping felt very fast, it would feel like “buzzing,” which correlates with roughness. P14 explained that he would score roughness higher if the “tapping” were present, which typically occurs at lower frequencies. P3 and P14 described that when the “tapping” was continuous or constant, which typically occurs at higher frequencies when movement is faster than perceivable, they would rate that as smoother. However, P0 explained that, during the speed condition, there could be conflicting sensations, saying that he would rate the sensation as rougher because of the “pulsing event”, but less rough because of the unrealistic movement on the palm. During the movement speed condition, participants were presented with four distinct speeds. At higher speeds, such as 73.2mm/s and 207.3mm/s, phenomena such as “tapping” or “buzzing” were common due to the inability to feel the perception of movement. These results suggest that we can at least partially convey tactile sensations’ roughness by modulating the speed of a focal point.

Locality. Participants reported different roughness sensations for different areas of the palm. P11 and P6 described that tactile sensations on the fingertips felt rougher. P2 and P3 explained that roughness depended on the amount of area they felt feedback. P8 described the symmetry of the sensations, explaining that “...the rough surface is, it is something that it is kind of normal and asymmetric” and used symmetry to determine roughness. Participants noted a correlation between roughness and actuated area. P4 suggested the feeling of ’static’ (i.e. static white noise) as initially something that covers a vast area and feels smooth, but that could be rougher as long as it did something dynamic. An example would be moving over a large area on the palm, which was agreed upon by P0 but not by P3, who correlated traversal with smoothness. P3 added that if the actuated area was not extensive enough, then that did not seem realistic, and thus, he would not rate it as rough.

3.3.4 Discussion

Study 3 investigated the roughness-modulating capabilities of the following parameters: the movement speed of a focal point, the direction of movement, the number of focal points, the distance between focal points and inter-element spacing. In this study, the participants could feel a total of seventeen unique sensations (each parameter with its levels), which were repeated three times totalling 51 roughness scores per study for a single user.

> **H1** Rougher sensations will be perceived if the direction of focal point movement is directed to more sensitive parts of the palm because that will enhance perceived tactile intensity.

H1 assumed that the direction of movement could alter the perception of roughness since different directions would actuate different parts of the palm. Each direction covers different parts of the palm, e.g. vertical would cover a substantial area where the fingers reside. The horizontal would cover mainly the middle of the palm, and the right diagonal would cover equally both the palm’s and the fingers’ middle. However, the results suggested that was not the case. The direction of movement has been found statistically insignificant, and the calculated confidence intervals showed no significant difference between the varying directions. However, the qualitative data showed something different. The thematic analysis has filtered the interview responses down to three themes, where one of them is "Locality". Locality shows that multiple participants considered the location of a stimulus as an important factor in scoring roughness. Participants said they considered factors such as location, symmetry, actuated area and movement. But if the participants thought that location matters, why do the results show that that is untrue? The answer probably lies in the participants' factors: symmetry, actuated area and movement. Actuating asymmetric locations on the palm could indicate that the sensation derives from a rough surface, e.g. the chaotic sensation of touching gravel or sandpaper. The area could signify to the participant the size of the surface that could correlate to specific objects in the minds of a participant. Lastly, the action of moving an actuating point could be a significant factor since it could be treated by a participant as a non-normal sensation.

> **H2** Subjective roughness perception will increase if the number of focal points increases because that will create the illusion of a macroscopic texture.

H2 hypothesizes that increasing the number of simultaneous focal points will increase a participant's perceived roughness. The quantitative data statistical analysis did find the results to be significant, i.e. there is a pattern between the number of focal points and roughness. Further statistical analysis has shown that difference in roughness scores exists only when using a single focal point with respect to two, three or four focal points. This means that using more than one focal point can be enough to modulate roughness perception. It is also apparent from figure 3.16 that all levels of the aforementioned parameter are below the mean, which means that with respect to the rest of the parameters, the number of focal points produced only smooth sensations. These results disprove H2. However, the mixed results describe a different narrative on how this parameter behaves with respect to roughness perception. Firstly, using more than one focal point increases roughness, but that is true only in this study's static context. Second, by comparing figure 3.15 with figure 3.13 and figure 3.17 we can see that the results of figure 3.15 and the zero speed value of 3.13 are consistently under zero, i.e. they are felt as smooth. This comparison, combined with the realisation that was mentioned in the paragraph above (H1), can determine that the static context of the focal points causes them to feel smoother. This can be extended to explain the opposite, which is in parallel with some of the thematic analysis results, which is that the act of movement alone can increase perceived roughness.

> **H3** Perceived roughness will increase if the distance between focal points is increased because it will increase the gap between elements.

H3 hypothesizes that increasing the distance between focal points can increase the perceived subjective roughness by enabling the actuation of a greater area. The statistical analysis contradicts the results of the qualitative analysis, i.e. the data analysis has shown no statistical significance in the data, which means that there is no effect between the varying distances of the focal points. Still, participants explained in the Locality theme that the greater area should have been able to convey a rougher texture. Nevertheless, there seems to be no further indication of any effect on distance between focal points.

> **H4** Subjective roughness will increase when the inter-element spacing of a moving focal point is increased because a greater area of the skin will be indented.

Finally, H4 expects higher inter-element spacing in focal point movement to increase roughness perception. The statistical analysis has shown that the participant results are significant. Still, the pair-wise tests have shown significance only between two adjacent values, which also have a limited difference between them. The results of the inter-element spacing are all considered rough, but the variance between the different inter-element spacing does not provide a significant difference. Therefore this hypothesis is partially rejected.

3.3.5 Limitations

In the first study, the interviews did not investigate which sensations made the participants feel the way they did. Knowledge of the sensations' source would help define the correlation between user sensation and description. Furthermore, three participants could not fully feel the tactile feedback, possibly due to skin temperature, age or both. This could indicate a restriction on the population that can perceive complex tactile sensations with ultrasound haptics.

3.3.6 Summary

This study aimed at answering the following research aims: 1) Analyze the roughness-mediating capabilities of each parameter on its own separately and 2) Examine how participants score roughness when actuated with non-contextual tactile sensations from isolated parameters. The aims mentioned above can provide an answer to research question RQ2:

> **RQ2:** How do changes in speed, focal point number, movement direction, and inter-element spacing affect perceived roughness scores?

Based on the discussion section above, which examines our hypotheses, it can be concluded that parameters mentioned in RQ2, when used in isolation, can enhance roughness perception but not in the way that was expected. Only speed, focal point number and inter-element spacing have been found statistically significant in promoting different roughness levels. Additionally, each parameter has shown unique roughness levels, which has been speculated in the discussion section as probably the result of moving, or lack thereof, rather than the effect of a parameter in particular. This realisation simplifies ultrasound haptics in such a way as to enable roughness modulation just by allowing a participant to feel movement.

Participants were interviewed, and their interviews were thematically analysed. The thematic analysis promoted insight into the participants' minds regarding how they perceive roughness and score it. Their themes were filtered down to "Apparent intensity", "Frequency" and "Locality". Despite lacking material to touch, these themes show that participants still created personal qualities to identify roughness. A participant expects intense sensations to promote material roughness due to the lack of material. When a rough material should be present, a participant expects a fast-moving, frequent sensation rather than a slow one. Finally, a participant expects specific locations to be actuated or a certain size of palm area to be stimulated when emitting a rough sensation.

Even though this study was informative and thoroughly addressed the research question, it highlighted several areas for improvement. Participants in the interviews experienced difficulties verbalizing haptic sensations, which emerged as a limiting factor. If participants cannot recall or articulate their expectations of rough or smooth sensations, it hinders their ability to accurately assess the roughness of a sensation. To address this issue, the study in Chapter 4 will include a brief pre-interview session designed to enhance the participants' haptic vocabulary, thereby improving their ability to describe haptic sensations more effectively.

Additionally, this study examined each parameter individually, requiring participants to keep track of roughness levels. While this approach provided informative results and allowed for the isolated examination of each independent variable, it made it challenging to generalize the findings. A multivariate study could offer a more comprehensive understanding of the combined effects of multiple parameters. Future research will consider adopting a multivariate approach to better capture the complex interactions between different variables.

Chapter 4

Roughness Simulation Using Mid-Air Patterns

4.1 Introduction

Simulating roughness does not rely solely on recreating the realistic features of a rough object or surface. Perceiving roughness is a process that can be altered depending on the subjective thought processes of the one that perceives said object or surface. Such thoughts could be where someone feels a tactile sensation, e.g. the fingertips are more sensitive and thus provide more detailed roughness information. Additional thought processes such as how intense something feels or even the frequency that the skin is being displaced can be a modulating factor. All of these processes have been pointed out by study 2 in chapter 3. This chapter focuses on combining these thought processes and unifying them in *tactile patterns* that can produce distinct roughness sensations.

The patterns are simple in form; however, they contain different characteristics that integrate the thought processes mentioned above. Five patterns were created named: Concentric Circles (CC), Horizontal Lines (HL), Vertical Lines (VL), and Square and Asymmetric patterns. To create these patterns, we use a single focal point to traverse a standard series of three-dimensional coordinates. The results of study 2 in chapter 3 insisted that speed, or the act of movement itself, may allow the modulation of perceived roughness and thus the speed parameter was integrated. Each pattern was designed in a specific way, to feel as it is supposed to feel. However, not all patterns can be felt the same if the speed is kept the same. Therefore, the speed parameter was renamed to *speed magnitude*, i.e. patterns have two speeds: one that allows them to feel like static and another that allows the perception of movement on the palm.

This chapter consists of one study that uses the aforementioned tactile patterns to convey material roughness to participants. The study examines the pattern's ability to convey significantly different roughness sensations and analyses the enhancing effect of the speed magnitude parameter. This chapter aims at answering the third research question (**RQ3**).

4.1.1 Chapter Structure

Section 5.2 describes the design and experimental methodologies required for simulating roughness. The section contains one study that examines how can a focal points' speed magnitude and the pattern that it draws modulate the perceived roughness felt. The section explains the research aims of the study, the experimental methodology, the results of the study, a discussion of the results, a list of limitations and finally a summary.

4.2 Study 3: Mid-Air Patterns

4.2.1 Research Aims

This study combines the results from Study 1 and Study 2 into creating complex patterned tactile sensations. These sensations combine parameters such as speed magnitude and pattern asymmetry to create simulations of roughness. The first aim of this study is to investigate the role of speed magnitude in the roughness perception of a tactile pattern. The difference in the speed magnitudes can make a pattern seem moving or like it is static, creating two different rough sensations.

The second aim of this study is to identify how the pattern of a tactile sensation modulates a participant's perceived roughness. Different patterns require varying focal point locations or different techniques to feel in a specific way.

Last the third aim of the study is to analyze how participants interact and gauge the perceived tactile patterns. Feeling a pattern that expands the whole hand is a drastically different sensation altogether, making it unique from Study 2. Understanding in what area the participants focus when they are in contact with an intricate pattern allows a better understanding of which areas to focus on when designing a tactile pattern.

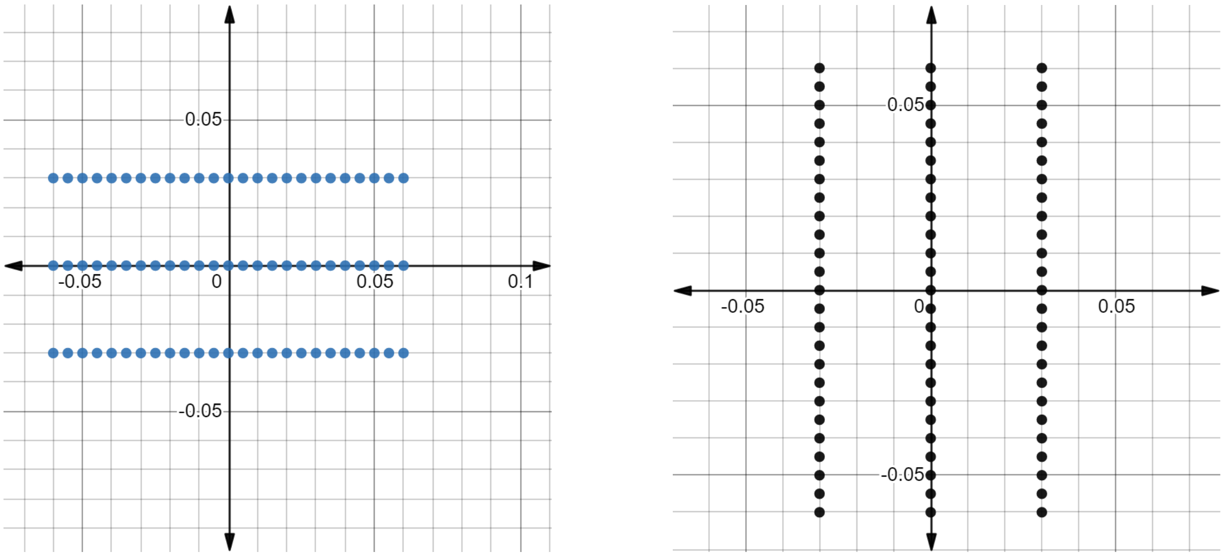
1. Investigate the role of focal point speed magnitude in roughness mediation.
2. Identify how a pattern design can affect roughness perception.
3. Examine participant interaction and area of focus when experiencing a tactile pattern.

These aims contribute an answer to the third research question (**RQ3**) of this thesis.

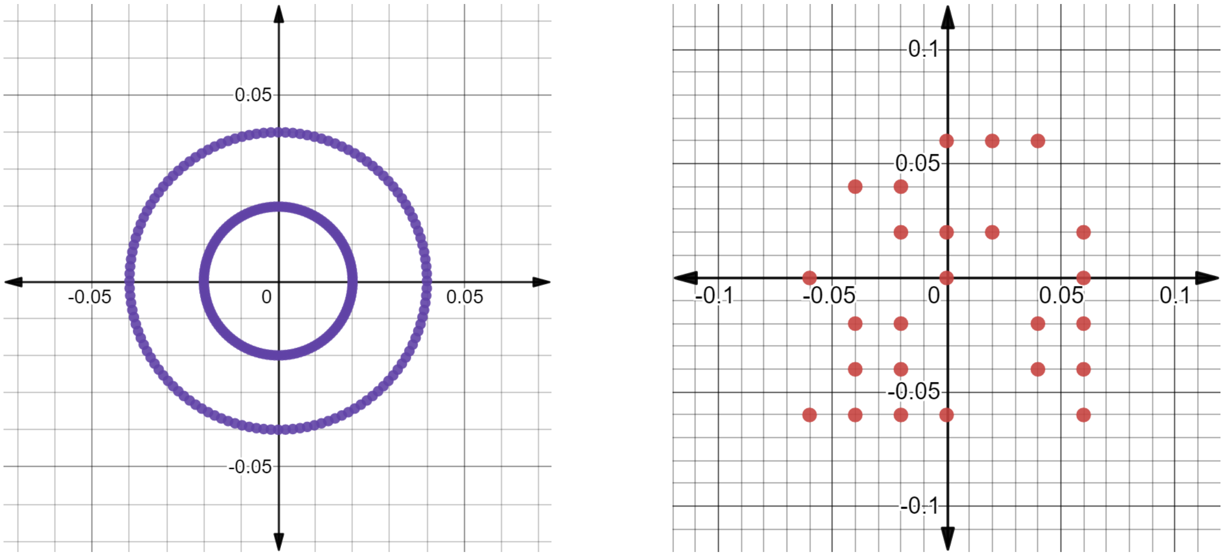
4.2.2 Methodology

Mid-air Patterns

The results of Study 2 influenced the generation of tactile patterns. Five patterns were designed: horizontal lines, vertical lines, concentric circles, squares, and an asymmetrical pattern (see figure 4.1). All patterns (apart from the asymmetrical pattern) are inspired by the works of Potier L. *et al.* [19]. The horizontal lines, vertical lines and concentric lines are drawable patterns, i.e. they need to be drawn in a specific way on the user's palm to feel as intended, whereas non-drawable patterns do not require any specific drawing route.



(a) Horizontal Lines (b) Vertical Lines



(c) Circles (d) Random

Figure 4.1: The five ultrasound haptic patterns that were studied in this work. From left to right: Horizontal Lines, Vertical Lines, Concentric Circles, Square, and Asymmetric. Each dot represents a focal point. The axes indicate the scale (in meters).

Speed can alter the roughness perception of the patterns. However, due to the unique design and techniques that are necessary to create ultrasound haptic patterns, we cannot use consistent speeds. Pilot studies showed that creating the horizontal pattern requires actuating 72 coordinates, but the concentric circles require 256. The difference in necessary actuated points makes it impossible to use the same speed values for all patterns. To keep a consistent perceived speed, we use the following speed magnitude (SM) values. All drawable patterns can have two-speed magnitude values: 1, which means that the patterns keep the preset amount of coordinates creating the illusion of a static pattern; and 3, where the patterns have three times as many points which slow down the focal point movement so a participant can recognize movement. Non-drawable patterns, i.e. the square and asymmetric patterns, do not implement the speed variable since slowing their drawing speed would lead to inconsistent moving sensations.

Horizontal Lines. The horizontal lines pattern features three horizontal lines distanced by 3cm in the y-axis. The lines have a total length of 12cm and width of $\approx$1cm and require a total of 72 focal points. Two design decisions played a role in creating a convincing horizontal line pattern. First, the lines should be actuated in parallel, e.g. for lines $f(x) = -3$, $f(x) = 0$ and $f(x) = 3$, their leftmost coordinates (-6,-3), (-6,0) and (-6,3) are actuated first, then the (-5, -3), (-5, 0), (-5, 3) and so on until they end at (6,-3), (6,0) and (6,3) and start over again. This actuation path ensures that there is minimal delay between drawing each separate line on the palm of the user and thus avoid vertically oriented animation effects. The second design decision was to avoid assembling the focal points in the form of a square and keep it as a rectangle that is longer on the x-axis. By doing so, it helps promote the illusion that the sensation is horizontally oriented.

Vertical Lines. The vertical lines pattern features three vertical lines distanced by 3cm on the x-axis. The lines have a total length of 12cm, and a width of $\approx$1cm and consist of 72 focal points. The vertical patterns follow the same design decisions as the horizontal lines but are inverted, i.e. coordinates are followed from leftmost to rightmost from top to bottom, and the rectangle area is more prominent in the y-axis.

Concentric Circles. The concentric circles feature two circles, $x^2 + y^2 = 4$ and $x^2 + y^2 = 16$, whose centre coordinates are at (0,0) and whose radius is 2 and 4 respectively. Each circle is composed of 128 focal points, giving a total of 256 emitting on the palm. We actuate the focal points in order of degrees, inner to the outer circle, i.e. starting at 0 degrees first the (2,0) coordinate of the inner circle is actuated and then the (4,0) of the outer circle, then at $\approx$ 2.8 degrees the respective (1.998, 0.0098) and (3.995, 0.196) are actuated and so on.

Square. The square pattern is a filled square of 6x6cm in size. The square is composed of a total of 9 focal points, 8 points representing the perimeter of the square and a single point in the centre. There is a 3cm space (horizontally or vertically) between each focal point.

Asymmetric pattern. The asymmetric pattern is a 25-focal point pattern with no specific shape or design. We created this pattern by pilot-testing multiple randomly created patterns. The generation of the random pattern is composed of the production of the square pattern of 49 focal points with 1cm spacing, shuffling all the coordinates and removing approximately half (24).

Measures

This study studies two IVs: pattern design and speed magnitude. Pattern design IV has five values: Horizontal Lines, Vertical Lines, Concentric Circles, Square and Asymmetric patterns. The speed magnitude IV has two values: Static and Motion-Conveying speed. The study has one DV: subjective roughness magnitude estimations.

Hypotheses

- **H1** Rougher sensations will be discerned when the sense of movement is perceived because the sense of movement itself promotes rougher sensations.
- **H2** Roughness scores will vary depending on the presented tactile pattern because depending on the pattern, different areas of the palm will be actuated.
- **H3** Rougher texture perception will be observed when focal points move in asymmetric routes because of the inability to infer repeating structural properties within a texture.

H1 hypothesizes that a single focal point a participant can perceive as moving in a specific pattern can convey rougher tactile sensations. Study 2 discussed that perceiving the movement in a focal point could be enough to convey feelings of roughness. This hypothesis addresses the aforementioned discussion by creating patterns that can be felt as “moving” or be “static”.

H2 hypothesizes that the pattern that a focal point moves is enough to alter the perception of roughness. Different patterns can cover different amounts of area, paths, and gaps between actuation and can actuate different parts of the palm, all of which contribute to modulating perceived roughness [1]. This hypothesis is tested by generating patterns similar to Potier L. *et al.* work [19].

H3 examines whether asymmetric patterns can convey rougher tactile sensations. Participants from the thematic analysis in study 3 have expressed that the asymmetric nature of some sensations convinced them to score a tactile sensation as rougher. This hypothesis is tested by creating an asymmetric pattern and a square pattern (the symmetric counterpart).

Testing the hypotheses

The available IVs are pattern design and speed magnitude. Pattern designs are categorical (nominal) data where the different patterns represent categories without inherent order. Speed magnitude is also categorical (nominal).

As a first step, data will be collected on roughness magnitude estimation scores for each combination of tactile pattern and speed magnitude. This is a repeated measures study, meaning that the same subjects are exposed to all conditions. After data collection, the dataset will be checked for missing data points and prepared for analysis.

To understand the basic properties of the data, summary statistics such as the median and interquartile ranges (IQR) for roughness scores across different tactile patterns and speed magnitudes will be calculated. Visual inspection of the data will be conducted using boxplots to observe the distribution of roughness scores.

Before deciding on the statistical tests to use, it is essential to verify the assumptions required for parametric tests. The Shapiro-Wilk test will be used to determine normality, and if normality is confirmed, Levene's test for homogeneity of variances will be performed. If the assumptions of normality and homogeneity of variances are met, parametric tests will be employed for their greater statistical power. Otherwise, non-parametric alternatives will be used.

For **H1**, which involves comparing roughness scores between two levels of speed magnitude (Static vs. Motion-Conveying speed), a related sample t-test will be used if the data meet the assumptions for parametric tests due to its ability to handle paired data effectively. If the data do not meet these assumptions, a Wilcoxon signed-ranks test will be used as it is a robust non-parametric alternative for paired comparisons.

For **H2**, which involves comparing roughness scores across the five levels of pattern design, a One-Way ANOVA will be used if the data meet the assumptions for parametric tests, as it is well-suited for comparing means across multiple groups. If not, a Friedman test followed by a post hoc Nemenyi test will be used, which is appropriate for non-parametric data with repeated measures.

For **H3**, which involves comparing symmetric and asymmetric patterns affected by speed magnitude, both IVs will be considered, leading to a factorial design. If the data are normally distributed, a Factorial ANOVA will be used to examine the main effects and interaction effects of the two IVs. For non-normally distributed data, an Aligned Rank Transform (ART) ANOVA will be used, which is suitable for non-parametric factorial designs.

Procedure

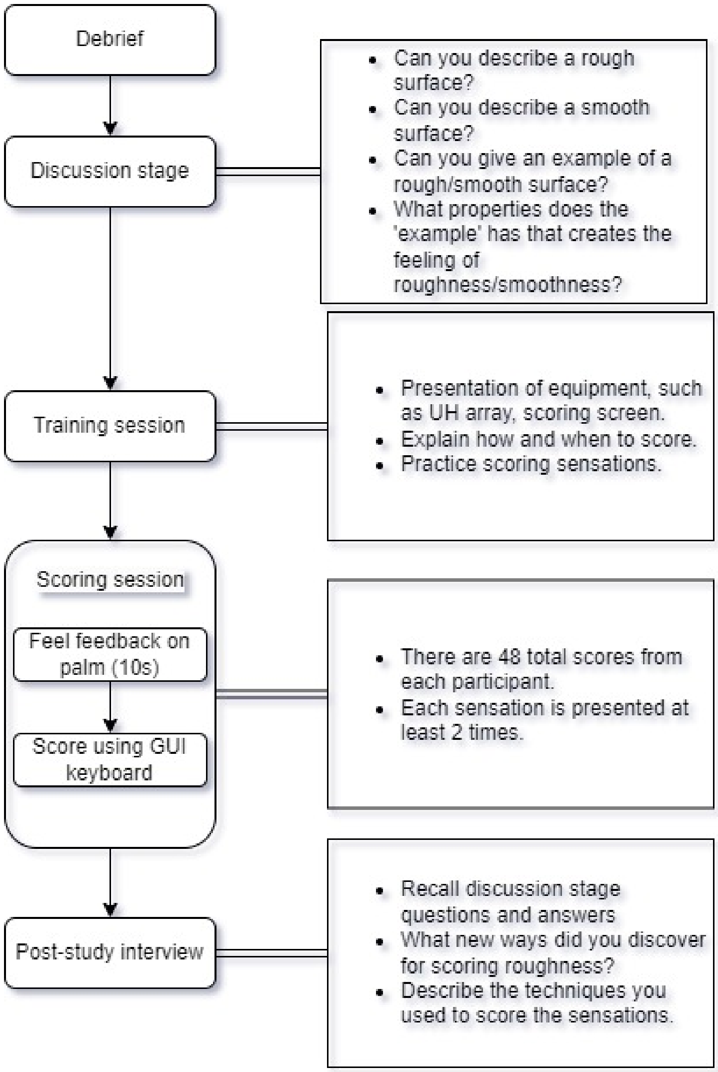


Figure 4.2: The figure presents the procedure each participant is required to attend in Study 3.

The study is split into three stages: a) Discussion stage b) Scoring stage and c) Interview stage (see figure 4.2). Initially, the participant conducts the discussion stage which aims to bootstrap the haptic vocabulary of the participant and help the participant remember what a rough or smooth sensation feels like. To accomplish those aims, the researcher asks the participant the following questions: "Can you describe a rough surface?", "Can you describe a smooth surface?", "Can you give an example of a rough/smooth surface?" and "What properties does the ’example’ has that creates the feeling of roughness/smoothness?".

The setup for the scoring stage is as follows. The participant sits on a 2m x 1m desk. The desk contains a stand where the participant can rest his right arm 12cm on top of the UHEV1. On the left, there is a screen with Graphical User Interface (GUI) where the user is informed when he is supposed to be feeling a sensation, when the sensation stops and when he has to add a score.

The GUI has a blue background, a white input field for the score and a white button for the user to confirm his input. When the user is feeling a pattern, the input field and confirm button become red coloured and disallow any input, thus forcing the participant to focus on the haptic sensation. Before initialising the scoring stage, the participant is presented with a five-minute training session where he experiences the tactile sensations and learns how to score. The stage ends when all sensations are scored.

The interview stage starts by asking the participant to recall what he said in the discussion stage. After recalling, the researcher asks the participant to explain whether he found any new ways to explain what a rough/smooth surface is and if after the experiment he realized any new properties that can describe a rough or smooth surface. Additionally, the participants are asked about their scoring techniques and are required to explain the process from the point they start feeling a sensation up to the point they confirm their score.

Participants

The study employed a total of 16 new participants, mostly students and staff from the University. All participants were over the age of 18 and were paid £5 for 40 minutes of a complete complete study session.

4.2.3 Results

These results are based on 720 roughness scores (magnitude estimations) from 16 participants. The roughness scores were first normalised. The Shapiro-Wilk test was conducted to assess the normality of the roughness magnitude estimation scores. The results of the test indicated that the data significantly deviated from a normal distribution, W = 0.97696, $p < 0.001$. Given the very low p-value, the null hypothesis of normality was rejected. This suggests that the roughness magnitude estimation scores are not normally distributed. This means that non-parametric tests needed to be employed.

Roughness Perception & Movement

Descriptive statistics were calculated to summarize the roughness magnitude estimation scores for each speed magnitude condition (Static and Non-Static), shown in table 4.1.

Speed	Mean	Median	Standard Deviation (SD)	Interquartile Range (IQR)
Non Static	0.410	0.4	0.290	0.458
Static	0.466	0.5	0.319	0.55

Table 4.1: Descriptive Statistics for Roughness Magnitude Estimation Scores by Speed Condition

To compare the roughness magnitude estimation scores between the two speed conditions (Static and Non-Static), a Wilcoxon rank sum test with continuity correction was conducted. This non-parametric test was chosen due to the lack of normality in the data distribution. The results of the Wilcoxon rank sum test indicated a statistically significant difference between the roughness scores for Static and Non-Static speeds (W = 54804, p = 0.02758). This suggests that the roughness magnitude estimation scores for the two speed conditions are significantly different. A boxplot representing the levels of speed magnitude can be seen in figure 4.3.

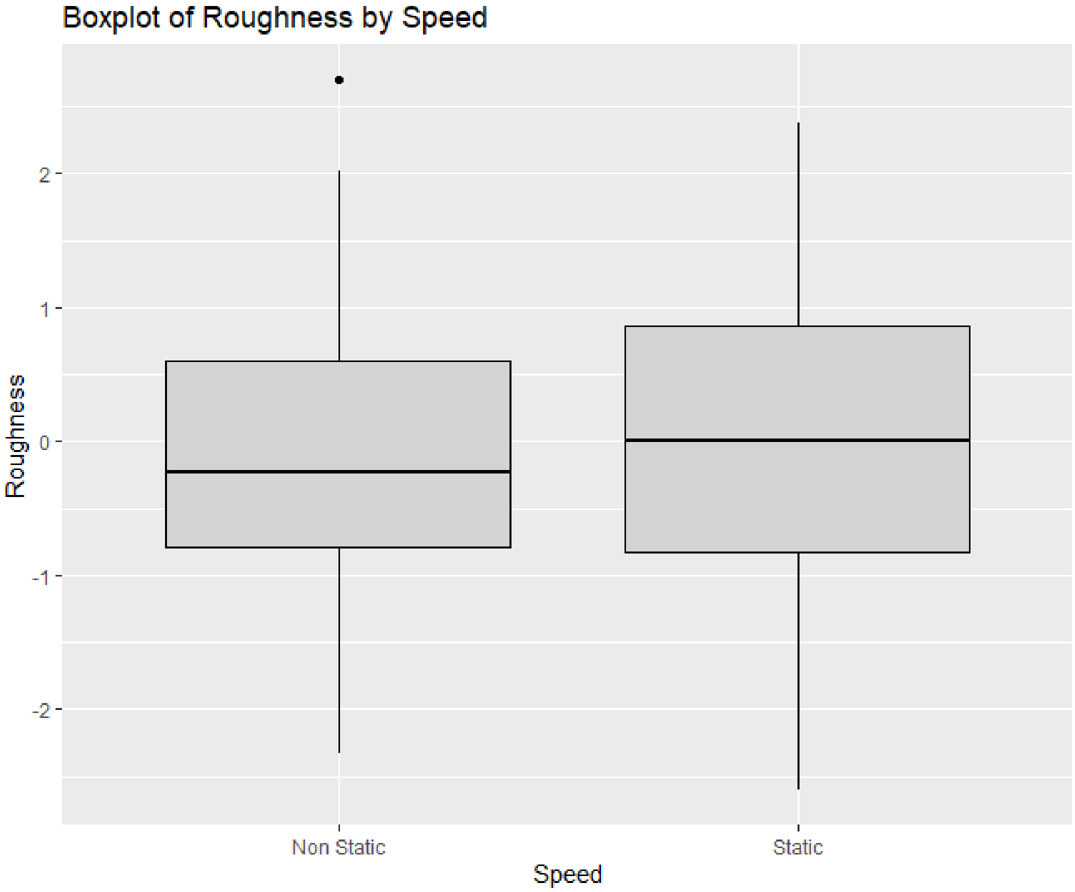


Figure 4.3: Boxplot depicting the roughness values on the y axis and speed magnitude values on x axis.

Roughness Perception & Mid-air Pattern

Descriptive statistics were calculated to summarize the roughness magnitude estimation scores for each pattern design. The results are shown in table 4.2.

Pattern	**Mean**	**Median**	**Standard Deviation (SD)**	**Interquartile Range (IQR)**
Assymetrical	0.763	0.8	0.196	0.246
Concentric Circles	0.697	0.735	0.234	0.278
Horizontal Lines	0.267	0.209	0.228	0.344
Square	0.247	0.2	0.223	0.314
Vertical Lines	0.312	0.293	0.225	0.375

Table 4.2: Descriptive Statistics for Roughness Magnitude Estimation Scores by Pattern

A Friedman test was conducted to determine if there were statistically significant differences in roughness magnitude estimation scores across different pattern designs. The results of the test produced Chi-Squared = 47.071, df = 4, and p-value < 0.05. Given the very low p-value, we reject the null hypothesis that the roughness scores are the same across all pattern designs, indicating significant differences in roughness scores between the patterns. A boxplot showing the interquartile ranges of the pattern is shown in figure 4.4.

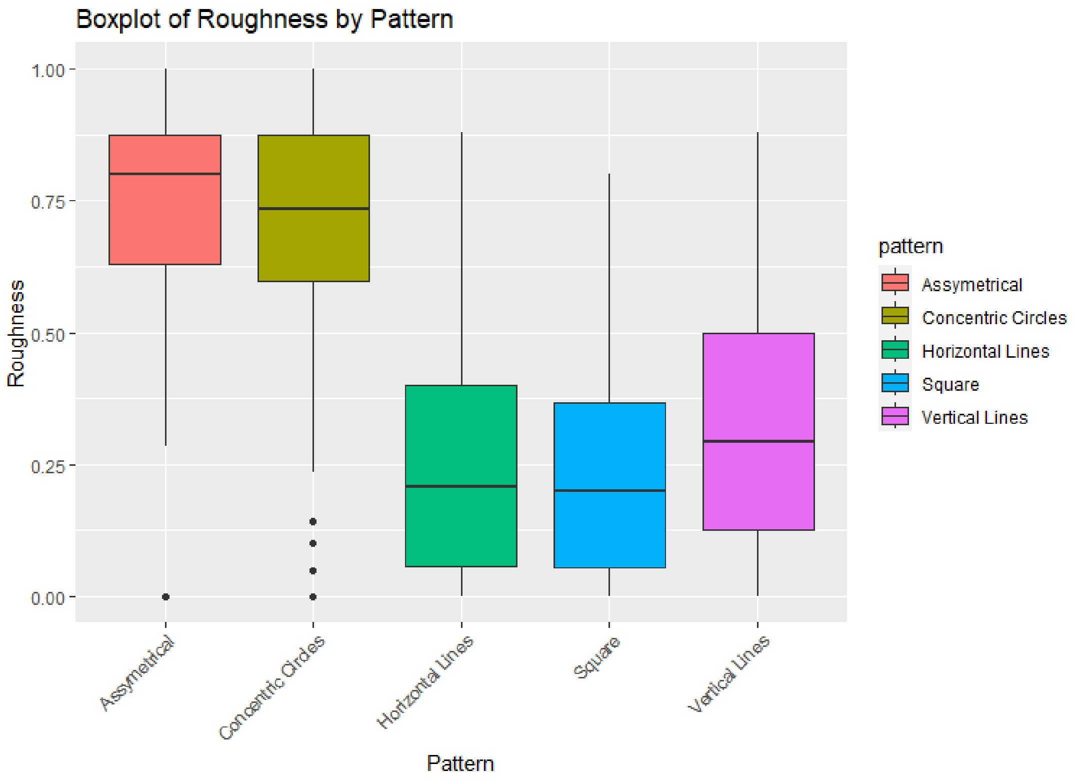


Figure 4.4: Boxplot depicting the roughness values on the y axis and mid-air pattern values on x axis.

Following the significant Friedman test, pairwise Wilcoxon rank sum tests with Bonferroni correction were performed to identify which specific pairs of pattern designs differed significantly in terms of roughness scores. The output of the test can be seen in table 4.3. Significant differences can be seen between Assymetrical and each of Horizontal Lines, Square, and Vertical

Lines. More significant differences can be seen between Concentric Circles and each of Horizontal Lines, Square, and Vertical Lines. Finally, no significant difference between Horizontal Lines and Square, Horizontal Lines and Vertical Lines, and Square and Vertical Lines.

Comparison	**p-value**
Assymetrical vs. Concentric Circles	0.26
Assymetrical vs. Horizontal Lines	< 2e-16
Assymetrical vs. Square	< 2e-16
Assymetrical vs. Vertical Lines	< 2e-16
Concentric Circles vs. Horizontal Lines	< 2e-16
Concentric Circles vs. Square	< 2e-16
Concentric Circles vs. Vertical Lines	< 2e-16
Horizontal Lines vs. Square	1.00
Horizontal Lines vs. Vertical Lines	0.36
Square vs. Vertical Lines	0.17

Table 4.3: Pairwise Comparisons of Roughness Magnitude Estimation Scores by Pattern with Bonferroni Correction

Effects of pattern design movement

The ART ANOVA was conducted to evaluate the main effects of pattern design and speed magnitude, as well as their interaction, on roughness magnitude estimations. The results are as follows, patterns: Df=2, DfRes=534, F-value=179.0363, p-value<0.05, speed: Df=1, DfRes=534, F-value=2.0061, p-value>0.01, finally pattern interaction: df=2, DfRes=534, F-value=2.4183, p-value=0.09. These results indicate a highly significant main effect of pattern design on roughness magnitude estimations, no significant main effect of speed, and a marginally significant interaction effect between pattern and speed.

Pairwise comparisons were performed to identify which specific patterns and speed conditions differed significantly in terms of roughness magnitude estimations. The Tukey method was used for p-value adjustment to control for Type I errors. The emmeans package in R studio was used to produce the estimated marginal means and pairwise comparisons for different patterns, speed, and interaction between speed and patterns. The marginal means for the patterns can be seen in table 4.4 and the pairwise comparisons in table 4.5. The results indicate no statistically significant interactions between pattern design and speed magnitude (all p-values > 0.05).

Pattern	Speed	Emmean	SE	df	Lower.CL	Upper.CL
CCircles	Non Static	270	16.4	534	238	303
H Lines	Non Static	255	16.4	534	223	288
VLines	Non Static	287	16.4	534	255	319
CCircles	Static	294	16.4	534	261	326
HLines	Static	272	16.4	534	239	304
VLines	Static	245	16.4	534	212	277

Table 4.4: Estimated Marginal Means for Roughness Magnitude Estimation Scores by Pattern and Speed

Contrast	Estimate	SE	df	t.ratio	p-value
CCircles Non Static - Horizontal Lines Non Static	14.97	23.2	534	0.644	0.9875
CCircles Non Static - Vertical Lines Non Static	-16.76	23.2	534	-0.721	0.9793
CCircles Non Static - Concentric Circles Static	-23.31	23.2	534	-1.004	0.9167
CCircles Non Static - Horizontal Lines Static	-1.06	23.2	534	-0.045	1.0000
CCircles Non Static - Vertical Lines Static	25.82	23.2	534	1.112	0.8765
HLines Non Static - Vertical Lines Non Static	-31.72	23.2	534	-1.366	0.7476
HLines Non Static - Concentric Circles Static	-38.28	23.2	534	-1.648	0.5670
HLines Non Static - Horizontal Lines Static	-16.02	23.2	534	-0.690	0.9831
HLines Non Static - Vertical Lines Static	10.86	23.2	534	0.467	0.9972
VLines Non Static - Concentric Circles Static	-6.56	23.2	534	-0.282	0.9998
VLines Non Static - Horizontal Lines Static	15.70	23.2	534	0.676	0.9845
VLines Non Static - Vertical Lines Static	42.58	23.2	534	1.833	0.4453
CCircles Static - Horizontal Lines Static	22.26	23.2	534	0.958	0.9308
CCircles Static - Vertical Lines Static	49.13	23.2	534	2.115	0.2809
HLines Static - Vertical Lines Static	26.88	23.2	534	1.157	0.8569

Table 4.5: Pairwise Comparisons of Roughness Magnitude Estimation Scores by Pattern and Speed

Thematic Analysis

The 2 hours of interview data were transcribed and analysed using thematic analysis. The thematic analysis started with forty-five codes which were sequentially analysed and filtered into eight sub-themes and finally organised into three themes: "Roughness Mediating Parameters", "Substitution Techniques" and "Difficulties".

Roughness Mediating Parameters. The pre-experiment interviews established the participants' understanding of roughness before completing the study. It was not surprising to find out that almost half of the participants had difficulties initially describing a "rough" or "smooth" surface. Most of them had to be encouraged to give an example of a rough or smooth surface to help them describe what properties or feelings define a rough or smooth surface. E.g. P9 identified a rough surface like a rock. After asking him what he could feel when touching a rock, he concluded that its robust nature made it rough (P3 also shared that opinion). Roughness was paralleled with the existence of obstacles when "gliding over the surface". Additionally, it was characterised as a surface that is unable to be bent or reshaped easily. Additionally, some users, e.g. P1 and P2, expressed that temperature was a significant factor. P0, P2 and P8 described roughness as unpleasant and smoothness as pleasant.

The post-experiment interviews identified participants' understanding of roughness after the study. P2 said that "...as the air was continuing I felt the air as hot and felt that the surface was rough. Also when I felt the air in my whole palm, it was thinner and colder and resembled a smooth surface". P0 did also score the sensations using pleasantness as a contributing factor.

Participants focused on the speed of the moving sensations (P0, P1, P6, P9, P10), or on the number of points felt on their palm (P0, P1, P5, P7, P8, P9, P10). Participants used the intensity factor to distinguish between two different similar sensations (P0, P1, P2). Last, some participants felt unintended sensations such as waves (P1, P2, P4, P9), which meant something different for them, e.g. P1 considered a wave to be neither rough nor smooth whereas P4 felt waves were part of a rough surface.

Substitution Techniques. Presenting the participant with a sensation that is not conveyed through material is confusing and uncanny. That is the case especially when a participant is not given any guidelines on how to judge such a sensation. However, participants did find unique ways of scoring these sensations. One of their ways was to use imagination, and P1 found a novel way to imagine macroscopic textures: "(I) imagine the hand is a monster truck. I would just imagine what would happen to the car if it was going through this type of surface...". P9 used his imagination to visualise the textures by imagining them as "raindrops" or a "whack-a-mole". P3 used his imagination to decide whether the sensation felt like a brick (rough) or fleece (smooth).

Some participants would initially try to determine the roughness of the sensations instinctively. This instinctive roughness scoring was either achieved by hastily counting the population of feedback points (P0, P2) or intuitively judging the quantity (P3). Some other participants required several (between four and nine) initial trials to differentiate between the feelings and assign roughness scores to them (P6, P7, P10). After their initial trials, their scores would typically be scored based on some form of metric or imaginative/instinctive paradigm. This behaviour correlates with past experiences; the participants' first scores are primarily based on past haptic experiences. Again, P3 is an excellent example because of her way of measuring roughness from an atomic experience, i.e. the feeling of a brick and fleece. By doing so, every sensation revolves around those experiences, and every additional information not fitting that description is noise.

Difficulties. Ultrasound cannot provide a powerful tactile force which, as a result, cannot correctly communicate the tactile features to the whole subject pool. This statement is evident in some participant responses: P0 mentioned that "it doesn't have any obstacles in the way, so I am confused". Also, P4 had difficulties feeling some sensations at all. Additionally, some participants did not have adequate knowledge or haptic vocabulary of what is the difference between a rough and smooth surface. E.g. P3 had great difficulty in translating her experiences with a rough brick or a smooth fleece to the sensations in the experiment. Issues such as lack of haptic vocabulary are common to participants in studies that use haptic feedback [54].

Conclusion. The conclusion in this analysis is that participants had found unfamiliar approaches to making sense of a complex sensory input. Some of the approaches intersect with one another, which can be the reason that a lot of tactile patterns are found sufficiently different in roughness scores. I noticed that participants have different opinions on what a rough surface is. This difference in opinion shows the subjectivity and unpredictability that a tactile surface/texture designer faces when designing such a complicated tactile sensation.

4.2.4 Discussion

Study 4 investigated the effects of perceiving tactile movement from a single focal point on varying patterns. Five patterns were emitted to the participants of this study and three of these patterns were conveyed as either static or moving. A total of 48 magnitude estimation roughness scores were recorded from each participant.

> **H1** Rougher sensations will be discerned when the sense of movement is perceived because the sense of movement itself promotes rougher sensations.

The results of this study disprove this hypothesis since the static speed is scored higher than its moving counterpart. However, the thematic analysis offers an explanation for the results. Participants mentioned that they would consciously attempt to quantify the speed of their palms as part of a criterion for roughness. This in turn means that some participants could recognise that different sensations had different speeds and used that knowledge to form a roughness score. This suggests limitations that will be discussed in the next section; however, these results also suggested that participants also use intense sensations, such as when feeling a very fast movement, to score the subjective roughness of a pattern.

However, it should be mentioned that the difference between Static and Non Static patterns is very small, which means for the scenario where mid-air patterns are employed to project the feeling of roughness, movement may not be the best roughness indicator.

> **H2** Roughness scores will vary depending on the presented tactile pattern because depending on the pattern, different areas of the palm will be actuated.

> **H3** Rougher texture perception will be observed when focal points move in asymmetric routes because of the inability to infer repeating structural properties within a texture.

H2 has been proven, with most mid-air patterns producing varying levels of subjective roughness perception. Furthermore, H3 can also be proven, as asymmetric patterns such as the asymmetric and Concentric Circles patterns have much rougher sensations. However, no interaction between patterns and the feeling of movement has been spotted. This could mean that it is not the feeling of movement in asymmetric patterns that causes the increased roughness perception, but rather the pattern in itself.

4.3 Limitations

A limitation of this study is the focal point speed parameter. This parameter was used to create the sensation of a static pattern or slow down so a participant could perceive the focal point movement. Details like participants trying to quantify speed suggest that some participants were able to distinguish the fast movement speed instead of feeling a static pattern. However, if that is the case nothing could be done to achieve greater speed since the static speed patterns were drawn at the maximum update rate allowed by the UHEV1. Therefore, this poses a limitation on the technology itself.

Furthermore, the **H3** hypothesis could have been explored in more detail. Firstly, the current patterns could be categorised as "symmetric" and "asymmetric" and generate an additional amount of asymmetric patterns so the results could more accurately infer that **H3** is proven.

4.4 Summary

This study and section aimed at answering the following research aim: 1) Investigate the role of focal point speed magnitude in roughness mediation. Speed magnitude was sued to create static or moving-feeling patterns. 2) Identify how pattern design can affect roughness perception. The featured study in this chapter generated five patterns to research this aim. Finally, 3) examine participant interaction and area of focus when experiencing a tactile pattern. Pre-study and post-study interviews were conducted to examine this aim. All of the aims mentioned above target to answer research question **RQ3**.

> **RQ3:** Does the use of basic ultrasound haptic patterns such as circles, lines, and dot arrays accurately simulate textures of varying levels of roughness?

Patterns such as circles, lines and dot arrays can help simulate roughness. Firstly, these patterns allow the manipulation of multiple parameters that can alter perceived roughness. One of the explored parameters, speed magnitude, was used to create the impression of static or moving patterns. This parameter produced significantly different roughness scores where the static-feeling patterns felt rougher than the slow-moving ones. This effect was consistent in all patterns. However, speed magnitude was not the only factor modulating the roughness score.

Pattern design was shown to have an effect on roughness scores. Concentric circles and the asymmetric pattern were considered the roughest of the patterns while the rest were consistently smoother. In the study above patterns such as the asymmetric and square were used to evaluate whether pattern symmetry played a significant role and indeed the two patterns were drastically different where the pattern was considered the smoothest and asymmetric the roughest.

Finally, the qualitative data were analysed and have shown three distinct themes of participant interaction and roughness evaluation. Participants have been found to seek quantifiable parameters so they can compare the mid-air sensations. Such parameters are pleasantness, speed, number of perceived points and waves. Also, participants used substitution techniques where they used previous experiences and let their imagination do the comparison by formulating scenarios such as traversing over the sensation felt or imagining that it feels like raindrops, etc.

Chapter 5

Multimodal Interaction with Mid-Air Textured Surfaces

5.1 Introduction

Ultrasound haptics can provide non-contact tactile sensation in three-dimensional space but actuates a weak shear force. Weak force can lead to users not feeling clearly the simulated textures due to the lack of skin displacement. Additionally, due to the weak sensations, necessary details can be missed by a user, degrading the haptic experience altogether. To overcome these issues, visual and audio stimuli can enhance the haptic experience by improving immersion and completing the missing details. Auditory stimuli can provide missing texture details through sound, and visual stimuli can enhance those missing details while contributing additional pseudo-haptic (visuo-haptic) phenomena.

This chapter contains two studies (Study 4 and 5) investigating the enhancement properties in texture discrimination of the audio, visual and combined audio-visual modalities. Study 4 uses virtual reality to immerse participants in a virtual world and uses audio-visual modalities with the realistically textured surfaces (mentioned in chapter 3, section 3.2) to examine the texture discrimination rates. Study 5 expands Study 3 by incorporating audio-visual modalities into the mid-air patterns and analysing the effect of those modalities regarding roughness perception. This chapter aims to answer the fourth research question (**RQ4**).

5.1.1 Chapter Structure

Section 5.2 and 5.3 describe the design and experimental methodologies required for integrating auditory and visual modalities to realistically textured mid-air surfaces and mid-air patterns, respectively. Each section will list the research aims, the experimental methodology, the study's results, provide a discussion of the results, list the limitations and finally produce a summary.

5.2 Study 4: Audiovisual Integration of Textured Surfaces

5.2.1 Research Aims

This study takes the results of study 1 and integrates its modalities in virtual reality. The two modalities that are integrated are audio-synthesized audio and realistic three-dimensional visuals. The study's first aim is to examine the effect of audio on roughness perception on realistically textured surfaces. Audio can inform a participant of the texture of a material. It is vital to understand how this material roughness perception is conveyed using ultrasound haptics.

The second aim of this study is to investigate the effect of realistic visuals on the roughness perception of textured surfaces. Visuals can help a participant visualise the felt tactile perceptions. It is crucial to understand whether the visuals overtake the sensation of the haptics, i.e. their contributing factor and whether any visuo-haptic phenomena are perceived.

Finally, the third aim is to analyse the effects of both audio and visuals together. The effects of three artificial stimuli simultaneously may force participants to choose which stimuli to utilise to discriminate the roughness of a tactile sensation or generate a combined understanding of all three.

The research aims above, intend to answer this thesis's fourth research question (**RQ4**).

5.2.2 Methodology

Measures

This study examines three IVs: textured surface, visual modality and audio modality. The textured surface had three values: Smooth (Flat at 64Hz), Semi-rough (Sine at 40Hz) and Rough (Knurl at 64Hz). There are three visual modalities: smooth paper, semi-rough paper and rough paper. Finally, the audio modality comprises smooth, semi-rough, and rough audio. There is one DV in this study: textured surface discrimination, whether a texture was correctly discriminated or not.

Hypotheses

1. **H1** Greater texture discrimination will be observed when corresponding audio prompts are introduced to textured surfaces because audio cues can infer texture information.

2. **H2** Improved texture discrimination will be observed when corresponding visual models are presented along with their respective textured surfaces because visual models can inform of missing textural properties.

3. **H3** Applying combinations of audio and visual modalities will improve texture discrimination by enriching the haptic experience with visual and auditory information.

H1 hypothesizes that increased texture discrimination can be observed when introducing audio prompts that promote the corresponding texture. This is in line with the related research work of V. Jousmaki *et al* [77] who have shown that when relevant audio is used in relevant context to the action involved, it can enhance textural information.

H2 asserts that increased texture discrimination can be observed when introducing visual models in conjunction with the textured surfaces. The roughness-mediating properties of visuals have already been established by Ho *et al.* [5] who have shown that the shadow projection from the peaks within the peaks and valleys within visual models can have roughness-altering effects.

H3 posits that the integration of both auditory and visual modalities will result in a net positive effect on roughness discrimination by leveraging the beneficial impacts of each modality. Generally, the combination of visual and auditory stimuli yields a composite effect that is not equally distributed between the modalities. Specifically, visual input is typically more influential in mediating perceptions of roughness compared to auditory input.

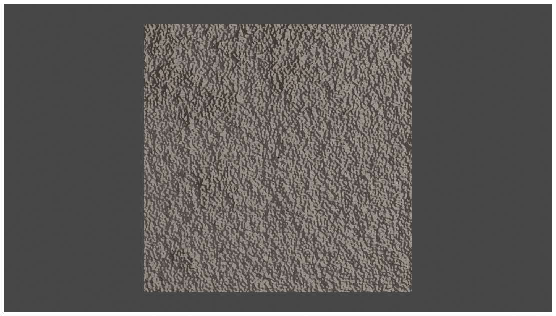
Visual Models

The visuals for this experiment take the form of three papers, each having a subjectively rougher surface (see figure 5.1). The reasoning behind the increasing roughness is to establish a mental connection with the roughness scales of the UGTs that will be used. The visuals are 3D models generated using the open-source Blender tool. To create the papers, a square plane was created, and its mesh was subdivided eight times into a 256x256 array. To create a rougher texture, a displacement modifier is applied and its strength is adjusted. The main difference between the three models is the strength value where the smooth texture (Figure 5.2a) has a value of 0.05, the semi-rough (Figure 5.2b) has 0.15, and the last the rough (Figure 5.2c) has 0.25. All models are coloured white, and their shadings are generated by external tools that incorporate the models, e.g., the Unity engine generates the shades in this case.

Audio-synthesized cues

The audio cues were initially high-quality recordings of a hand traversing over a watercolour paper of increasing roughness. The papers used are Waterford 300GSM Hot Pressed for a smooth texture, Waterford 300GSM Cold Pressed for a semi-rough texture and last, Waterford 300GSM

(a) Smooth model (b) Rough model



(c) Irregular model

Figure 5.1: Visual models created in Blender.

Rough for a rough texture. Even though the audio quality was adequate, the process of outputting the sound to the user was unrealistic, which would reduce the participants' immersion in the virtual environment. Therefore, it was decided to try and audio-synthesize the audio cues.

To do so, a tool was needed that could be used alongside the Unity framework, and that tool was the Pure Data Programming Language [153]. The first action before developing audio-synthesized cues was to analyze the preexisting audio files from the watercolour papers and inspect their spectrogram to identify how paper traversing can be generated and whether texture roughness affected different parts of the frequency spectrum. The spectrogram generation and examination were performed using the application Wavelab [154]. By examining the spectrogram of the audio recordings, it was identified that traversing over a paper created sounds in the whole spectrum equally with lower intensity at the start and end of the traversal. In addition to that, it was noticed that the only difference between increasing texture roughness was that rougher textures had greater amplitude in the spectrogram throughout the spectrum.

The information from the spectrogram was the basis for developing the audio cues. The plan for creating the audio cues was to use white noise, which is the emission of sound in the whole spectrum, and amplitude modulate it with a cosine wave. We created three different audio cues for smooth, semi-smooth and rough audio. To achieve that, the Pure Data patch (a patch is a series of tonal commands that output a specific sound) was configured to increase the amplitude for rougher textures by 20% for every level, i.e. if smooth audio is at 20% of the digital to analogue converter, then the semi-smooth is at 40% and rough at 60%. Last, to increase the realism of the audio, a technique was used that stopped the audio cue and restarted it with phase 1 and stopped it 850 ms later, thus producing a simulation of the stopping sound.

Procedure

The experiment is divided into three iterations, each exploring a different combination of dependent and independent variables. In each iteration, one of the independent variables - audio, visual, or audio-visual - is changed. The iteration is further divided into two stages: (a) the exploration stage where the user memorizes the textures, and (b) the test stage where the user is evaluated on their ability to differentiate between the textures.

In the exploration stage, participants are encouraged to explore and memorize the various textures. Each textured surface is presented for a maximum of 90 seconds in a virtual reality environment. Participants can feel the texture by using a virtual hand to touch the paper in front of them. This stage consists of three iterations and may include audio cues, visual variations, or both to enhance the experience.

In the test stage, participants are required to touch the texture in front of them for up to thirty seconds and then select their preference by pressing a virtual button. This action saves their selection and moves on to the next texture, changing both the audio/visual/audiovisual cue and the textured surface. There are a total of 18 textures that appear randomly during this stage, resulting in 54 textures in total for the participants to be tested on. To ensure fairness, counterbalancing measures are applied. Participants were split into three groups, and each group performed the iteration in a different order: group One (Audio - Visual - Audiovisual), group Two (Audio - Audiovisual - Visual) and last group Three (Visual - Audio - Audiovisual). The test stage concludes with a brief questionnaire about the participants' haptic perception of the textures. This stage takes place in the same virtual environment as the exploration stage.

5.2.3 Participants

The study recruited fifteen participants who were healthy young adults between the ages of 18 and 35. The majority of the participants were staff or students at the University of Glasgow. Each participant was paid £6 upon completion of each one-hour session.

5.2.4 Results

By analyzing the data using a confusion matrix, the following data have been produced. The overall accuracy by combining results from audio, visual and audiovisual tests has been measured to 56.34% (P-Value < 0.01) and the class statistics have shown that the smooth texture (ST) had 75.69% sensitivity, semi-rough texture (SMT) produced 48.63% sensitivity and last

Modality	P-Value	Overall	ST	SMT	RT
All	<0.01	0.5634	0.7569	0.4863	0.4471
A	<0.01	0.4306	0.6111	0.375	0.3056
V	<0.01	0.6259	0.8778	0.4667	0.5333
AV	<0.01	0.6057	0.7527	0.5914	0.4731
A (Overpower)	**>0.01**	0.3802	0.4237	0.4	0.3235
V (Overpower)	**>0.01**	0.3037	0.3444	0.2889	0.2778
AV (Overpower)	**>0.01**	0.3644	0.36	0.3733	0.36
Group 1 (All)	<0.01	0.6852	0.7889	0.5778	0.6889
Group 1 (A)	<0.01	0.5	0.6	0.4333	0.4667
Group 1 (V)	<0.01	0.8	0.9	0.6667	0.8333
Group 1 (AV)	<0.01	0.7556	0.8667	0.6333	0.7667
Group 2 (All)	<0.01	0.4852	0.7222	0.4333	0.3000
Group 2 (A)	**>0.01**	0.3556	0.6000	0.3333	0.1333
Group 2 (AV)	<0.01	0.5889	0.7333	0.6333	0.4000
Group 2 (V)	<0.01	0.5111	0.8333	0.3333	0.3667
Group 3 (All)	<0.01	0.5263	0.7895	0.4211	0.3684
Group 3 (V)	<0.01	0.5667	0.9000	0.4000	0.4000
Group 3 (A)	**>0.01**	0.4444	0.6667	0.3333	0.3333
Group 3 (AV)	**>0.01**	0.5111	0.6667	0.5333	0.3333

Table 5.1: Here are the statistics for Experiment B, broken down by texture and modality. The modality column indicates whether it was audio (A), visual (V), or audiovisual (AV). The first column shows the modality, the second shows the p-value, and the third shows the accuracy for all textured surfaces. The fourth, fifth, and sixth columns present the accuracy for smooth texture (ST), semi-rough texture (SMT), and rough texture (RT), respectively.

the rough texture (RT) produced 44.71%. The confusion matrix for the results is shown in Table 5.2. Analyzing by modality has shown audio-synthesized cues produced an accuracy of 43.06% (P-Value < 0.01, ST: 61.11%, SMT: 37.5%, RT: 30.56%), the visuals produced 62.59% (P-Value < 0.01, ST: 87.78%, SMT: 46.67%, RT: 53.33%) and the audiovisual produced 60.57% (P-Value < 0.01, ST: 75.27%, SMT: 59.14%, RT: 47.31%).

Actual\Predicted	*RT*	*SMT*	*ST*
RT	110	82	28
SMT	96	115	28
ST	31	40	181

Table 5.2: Confusion matrix for Study 4 results. The horizontal categories list the predicted textures, while the vertical show the actual ones.

The collected data has been investigated further by understanding whether the modalities overpower the textured surfaces. In order to do that, the data were analyzed assuming that the modalities' appearance or sound (or both) were the correct answers that the users had to make. Applying the modalities "roughness" factors as the correct answers the following results are produced: The audio modality produced an overall 38.02% (P-Value > 0.01, ST: 42.37%, SMT: 40%, RT: 32.35%) accuracy, video 30.37% (P-Value > 0.01, ST: 34.44%, SMT: 28.89%, RT: 27.78%) and audiovisual 36.44% (P-Value > 0.01, ST: 36%, SMT: 37.33%, RT: 36%).

Questionnaires & Qualitative data

Two questionnaires were needed to complete the experiment. The first questionnaire needed to be completed by the participant the first time he would finish an exploration stage. The questionnaire focused on open-ended questions based on the participants' opinions on textural words, feelings, sensations and associations that could describe a textured surface. The second questionnaire was more concerned with QUIS-style questions focused on ease of identification, texture roughness, ease of tasks, overpowering opinions, whether the textures seemed realistic and general comments about the experiment.

When the participants finished their first iteration (exploration and identification test) they were presented with the first questionnaire. When the participants were asked to provide textural words, feelings, sensations and associations, the following results have been gathered: texture A (ST) was described 7 times as air and 5 times as smooth. Texture B (SMT) was mentioned 4 times as air and 2 times as rough. Texture C (RT) was mentioned 5 times as air, 4 times as rough and 2 times as a fan.

By the end of all iterations, the second questionnaire needed to be completed. In the first question, the participants needed to choose between 1 (difficult) to 9 (easy) for how difficult or easy each texture was to identify. Texture A (ST) produced an average of 7.14 (SDev: 1.79), texture B produced 5.79 (SDev: 2.22), and C produced 5.57 (SDev: 1.74). In this question, it was mentioned as additional comments five times that B and C were hard to distinguish, where some additional comments specified between B and C being more identifiable than the other.

The second question asked the participants about their opinion on how rough (1) or smooth (9) was each texture which resulted in texture A (ST) being 8.5 (SDev: 0.65), B (SMT) being 3.57 (SDev: 1.78) and last C (RT) being 3.36 (SDev: 2.27).

After that, the participants were queried about the difficulty (1 = difficult, 9 = easy) of each iteration, i.e. first, second, and third. Since the participants were tested in different based on their grouped, the results were matched correctly and produced the following results: Audio 4.93 (SDev: 2.44), Visual 6.17 (2.14) and Audiovisual 6 (SDev: 1.98). As additional comments, some participants stated that by the end of the experiment, they felt that they had a better grasp of identifying the textures. One stated clearly that the visual aid helped him to identify textures, and another participant stated that the audio helped him identify the textures.

In addition to that, participants were queried whether they felt that audio, visual or audiovisual modalities overpowered the textures. The results from the 14 correctly answered questionnaires for this answer show that 9/14 participants believe that audio overpowered the textures, 5/14 believed visual overpowered them, and 6/14 believed the audiovisual cues overpowered them.

The users were required to answer if the audio, visual or audiovisual modalities made the textures feel more realistic. The results show that 7/14 participants believed audio made the textures feel realistic, 11/14 believed video made the textures realistic, and 11/14 believed audiovisual did.

5.2.5 Discussion

Study 4 investigated the effects of audio and visual modalities in discriminating textured surfaces. In this study, the participant could perceive three different textured surfaces in combination with three visual models and three audio-synthesized cues. The study intended to answer three research questions which will be discussed below.

> **H1** Greater texture discrimination will be observed when corresponding audio prompts are introduced to textured surfaces because audio cues can infer texture information.

Given the confusion matrix results, it is visible that when participants were tested with only the audio-synthesized sound as the additional modality, the overall discrimination rates were reduced when compared with the Study 1 results. Given the three groups of participants, the second and third groups have produced statistically insignificant results in the audio sage. Additionally, participants reported that the audio stage was the hardest of the three, scoring 4.93 (1 = difficult, 9 = easy). Finally, 9/14 participants believed that the audio overpowered the other modalities. Given the above results, it is indicated that audio presents an additional difficulty and can overpower the other modalities making texture discrimination unnecessarily difficult. In summation, realistic textures with simple audio-synthesized cues negatively hinder a participant's ability to recall and discriminate the sensation of a textured surface. From the literature review, it was already known that the effect of audio in haptics can have only minor effectiveness; however, audio in ultrasound haptics can have negative results.

> **H2** Improved texture discrimination will be observed when corresponding visual models are presented along with their respective textured surfaces because visual models can inform of missing textural properties.

Overall, visuals have produced positive results in the discrimination of textured surfaces compared to the Study 1 results. Except for the semi-rough textured surface, both smooth and rough-textured surfaces exhibited increases in the participants' discrimination rates. Participants found that the difficulty of the visual stage was easier than the audio and similar to the audiovisual. Additionally, 5/14 participants believed that the visual modality overpowered them. The results suggest that the visual modality has a net positive impact on texture discrimination and felt less overpowering compared to the audio modality.

> **H3** Applying combinations of audio and visual modalities will improve texture discrimination by enriching the haptic experience with visual and auditory information.

The results for the audiovisual stage seem to exist between of the two modalities. Even though the audiovisual seemed as easy as the visual stage, it scored lower accuracy than the visual stage, and 6/14 participants thought the combination of audio and visuals overpowered them. As discussed earlier, the audio modalities used seem to worsen the discrimination capabilities of the participants, and it is possible that the combination of multiple modalities overburdened the decision capabilities of the participants.

5.2.6 Limitations

The main limitation of the study was the quality of the audio-synthesized cues. If the cues had been more convincing, the results would have been closer to 50%, which is equivalent to random chance. However, the findings revealed that the audio cues consistently decreased discrimination values, falling as low as 30.5% for the Rough textured surface. Based on the current understanding, the audio cues should have been more intricate, instead of merely increasing their amplitude. In Study 5, the cues will be more thoroughly analyzed using a superior microphone and a more advanced spectrogram to accurately simulate the expected audio from the participants.

5.2.7 Summary

This study attempted to combine textured surfaces from Study 1 with audio, visual and audio-visual modalities in an attempt to understand the impact of those modalities on discrimination rates. This understanding is essential to answer the fourth research question, **RQ4**.

> **RQ4** How do audio-visual modalities improve roughness perception of ultrasound-generated sensations?

According to the study, using visual cues can enhance the ability to distinguish textures on surfaces created through ultrasound haptic technology. It's important to note, however, that not all textures benefit from this method. For instance, the Knurl texture actually performed worse when combined with visual cues. This indicates that there may be unknown factors within the textures that affect the effectiveness of visual cues. One possible factor could be how the texture is designed - if the perceived texture doesn't match the visual cues, it could lead to confusion and inaccurate discrimination.

5.3 Study 5: Audiovisual Integration of Mid-air Patterns

5.3.1 Research Aims

The first aim of the study is to investigate the effect of high-fidelity visual models with varying roughness values on mid-air patterns' roughness scores. Rougher visual models should be able to promote rougher roughness scores to the participants.

The second aim is to investigate the effect of audio-synthesized cues on roughness scores of mid-air patterns. The three types of audio cues try to mimic sandpapers of different grit values. The rougher auditory cues are expected to promote rougher roughness scores.

Finally, the third aim is to investigate the roughness scoring methodology of each participant. The previous studies have shown that participants used alternative sources of texture information to decide upon a roughness score, such as quantifiable values (amplitude, speed, frequency), previous experiences and comparisons with real objects (fleece, bricks). By giving the participants another source of information, it is expected that the participants will use both the tactile and audio/visual/audio-visual information available to complete a roughness score.

5.3.2 Methodology

Measures

This study studies three IVs: mid-air patterns (from Study 3), visual modality and audio modality. The mid-air patterns had five values: horizontal lines, vertical lines, concentric circles, squares, and an asymmetrical pattern. There are three visual modalities one representing a smooth paper, a semi-rough paper and a rough paper. Finally, the audio modality is comprised of smooth audio, semi-rough audio and rough audio. There is one DV, the roughness estimation score.

Hypotheses

> **H1** Increased roughness scores will be observed when rougher-looking visual modalities are shown due to the rougher visuals addressing textural information deficiencies.
>
> **H2** Increased roughness score will be observed when rougher-sounding audio cues are triggered because the audio will provide roughness information.

Both **H1** and **H2** extend the investigations conducted in Study 4 by examining the same hypotheses within a different context. In this instance, the medium of roughness is mid-air patterns rather than realistically textured surfaces. Preliminary results from mid-air patterns (Study 3) have shown promising potential for mediating roughness perception. However, further understanding is required to elucidate the effects of auditory and visual stimuli on the perceived roughness scores of these mid-air patterns.

Testing the hypotheses

The available IVs are mid-air patterns, visual modality, and audio modality. Mid-air patterns are categorical (nominal) data where the different patterns represent categories without inherent order. Audio and visual modalities are ordinal data, with categories that have a logical order of increasing roughness. Both H1 and H2 can use the following statistical testing plan, given that the audio and visual IVs have the same data type.

When the results are collected, descriptive statistics will be presented to summarize the data. This will be followed by a three-way ANOVA to assess the main effects and interactions among the IVs, provided the assumptions of ANOVA (normality, homogeneity of variance, independence, and random sampling) are not violated. If the ANOVA indicates significant effects, a Tukey's HSD post-hoc test will be used to identify specific group differences.

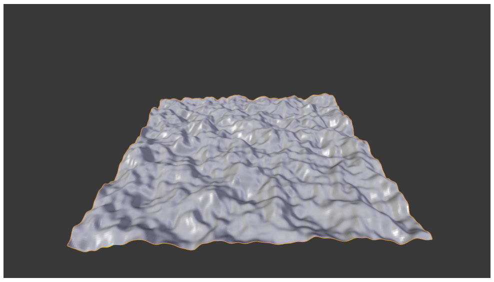
If the assumptions for ANOVA are violated, a non-parametric alternative, the Kruskal-Wallis test, will be used. This will be followed by a post-hoc Nemenyi test to determine significant differences between groups. Normality will be assessed using a Shapiro-Wilk test and if normality can be assumed, the homogeneity of variance will be evaluated using Levene's test.

Visual models

Three visual models were used throughout the experiment, each representing a smooth, rough and irregular surface. The three visual models are depicted in figure 5.2. To create the previously mentioned visual models, the Blender software was utilised. To create the models, first, an empty plane (scaling 1,1,1) needs to be created and placed in the centre coordinate (0,0,0). Then to produce the roughness effect the Noise Pack v1.0 is used, and in this case, a regular noise generator is applied to the plane. In order to alter the visuals' roughness value, the shader's scale parameter needs to be configured. The scale parameter adjusts the size number of bumps that exist on top of the plane. Finally, a light source must be created to create the shadows. The smooth model used a scaling of 5, the rough used 0.7 and the irregular used 0.2. Finally, exporting these models to Unity requires rendering the models at the highest resolution, creating a plane model in Unity and applying the render model to the Unity plane.

(a) Visual of a smooth paper.

(b) Visual of a semi-rough paper.



(c) Visual of a rough paper.

Figure 5.2: The three visual modalities used in the study represent a smooth, semi-rough and rough visual.

Audio-synthesized cues

The experiment required the generation of audio-synthesised cues in order to convey the material roughness information to the participants. A collection of 12 sandpapers of varying grit values (120/220/320/400/600/800/1000/1200/1500/2000/2500/3000) were recorded and analysed using a spectrogram. Each sandpaper was recorded three times at three different speeds (slow: traverse the sandpaper in 1 second, medium: traverse the sandpaper in 0.5s, and fast: traverse sandpaper in 0.25s). The traversal was done using the right index finger. In previous years a similar recording was done (study 5 in 1.1) however it was later realised that the microphone that was used previously was not accurate enough to record smaller variances in amplitude. Therefore, this time a higher-fidelity microphone (miniDSP UMIK-1) is operated to record the audio. Additionally, to create the spectrogram for every recording a Jupyter notebook collection is used, which uses the “sounddevice” library to properly record the sounds (collects additional metadata), uses the “NumPy” and “SciPy” libraries for filtering and analysis and finally uses “Plotly” library to generate the spectrograms shown in figures 5.3, 5.4, 5.5, 5.6 and 5.7.

Analyzing each spectrogram revealed certain auditory details that could be replicated programmatically. Firstly, the faster the traversal, the fewer details are visually apparent. This can be seen in figures 5.3, 5.4 and 5.5 where the high-frequency amplitude drops and the low amplitude lines are disappearing and become louder as the traversal becomes faster. Furthermore, the rougher sandpapers 120, 220, and 320 have shown repetitive low-amplitude vertical lines (shown in figure 5.6). Furthermore, the smother sandpapers like 1000-3000 have shown high-amplitude horizontal lines at specific frequencies. All of the details mentioned above were taken into account when generating the audio-synthesized audio for the experiment.

Pure Data (PD) software was used to create the audio-synthesized audio. PD can programmatically generate audio by creating midi notes at varying frequencies and applying filters upon them, with the results being a “patch” file that can accept parameters to expand its audio-generating capabilities further. These patch files need to be connected to the experiment software (which is set up in Unity) a wrapper library needs to be integrated to allow that connection. To accomplish this, the LibPdIntegration library is used, which at the moment, is the only library that can still work on Windows machines.

The recordings of 120, 1000 and 2000 grit value sandpapers were chosen for the experiment. Grit 120 had repetitive vertical lines of low amplitude and two large horizontal lines of small-effect low amplitude, and the faster it moved, the louder it sounded. To accomplish these effects, a series of hard high-pass and hard low-pass filters (hard means there were six filters used back to back) were used to generate the horizontal lines between 1kHz-2KHz and 3kHz-5kHz. For the vertical lines, a cosine oscillator was used at 5.5Hz-11Hz (depending on hand movement speed) that outputted maximum volume at 1 and no volume at -1. Finally, to achieve the increased amplitude at higher speeds, I have set the minimum volume to 0.5 at the lowest hand speed (75 mm/s) and 1 at the highest (1000 mm/s). Grit 1000 and 2000 use the same methodology as grit 120 to create their distinct horizontal lines of low amplitude (1kHz-2kHz, 3kHz-5kHz and 6kHz-7kHz for grit 1000 and 1kHz-2kHz, 3kHz-4kHz). The amplitude-hand speed correlation is done with the same methodology as grit 120 for both grit 1000 and 2000, except that grit 1000 is 25% louder than the other two, so the starting value is 0.75. Finally, a wind-up/close-down methodology was added to increase the realism of the audio. When a user starts or ends a movement, there is a linear increase/decrease of volume to the specified amplitude (or back to 0) in 0.1s.

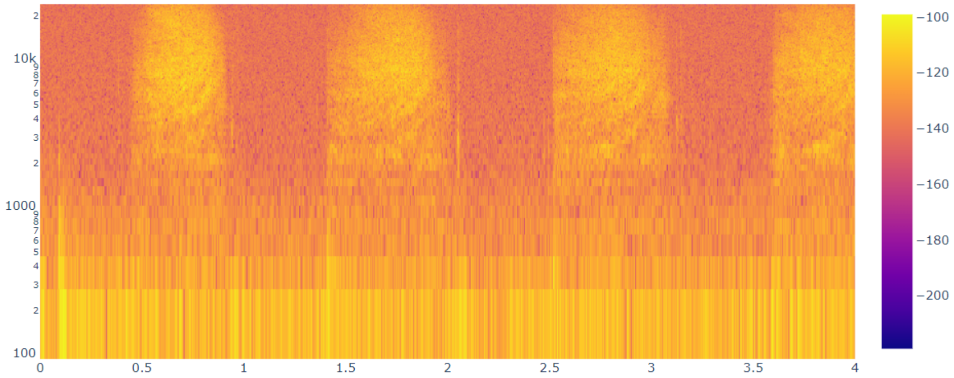


Figure 5.3: A temporal representation of 1 second recordings of a finger traversing over a sandpaper with grit value of 2000.

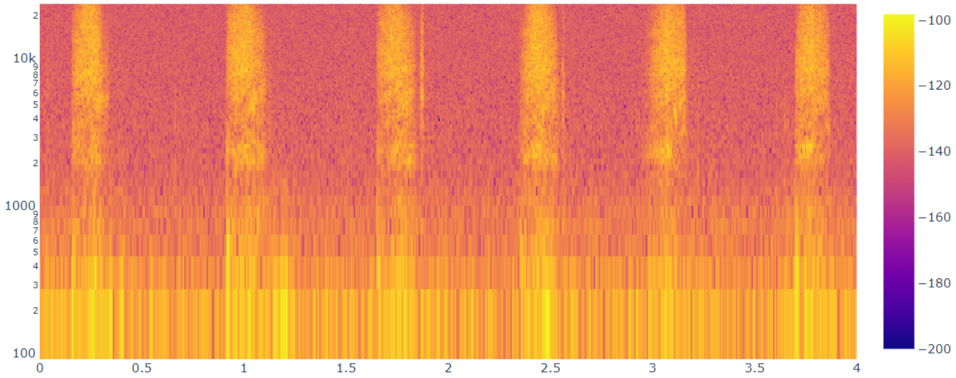


Figure 5.4: A temporal representation of 0.5 second recordings of a finger traversing over a sandpaper with grit value of 2000.

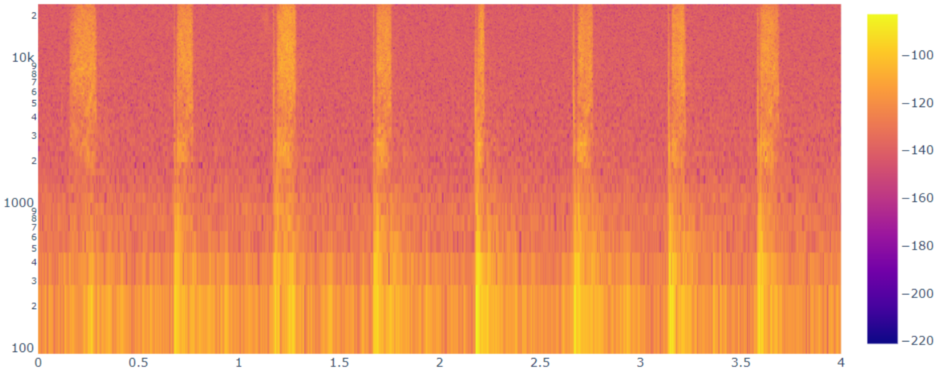


Figure 5.5: A temporal representation of 0.25 second recordings of a finger traversing over a sandpaper with grit value of 2000.

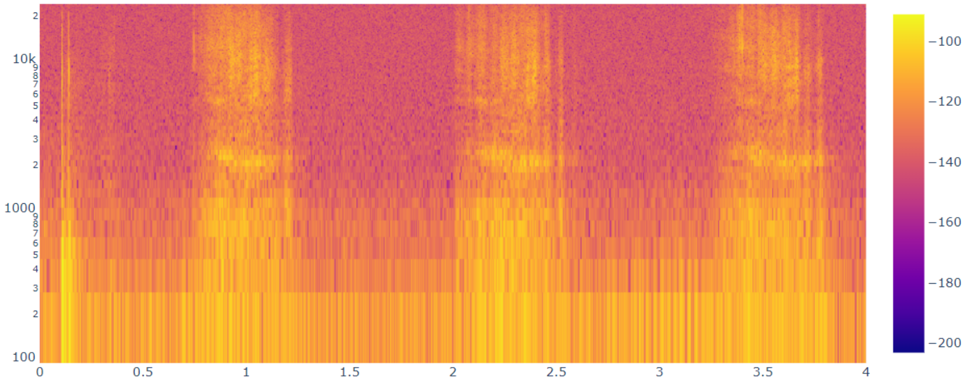


Figure 5.6: A temporal representation of 1 second recordings of a finger traversing over a sandpaper with grit value of 120.

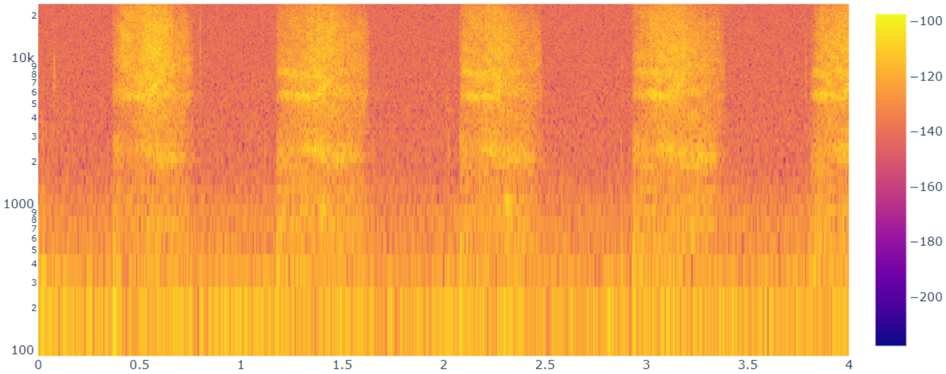
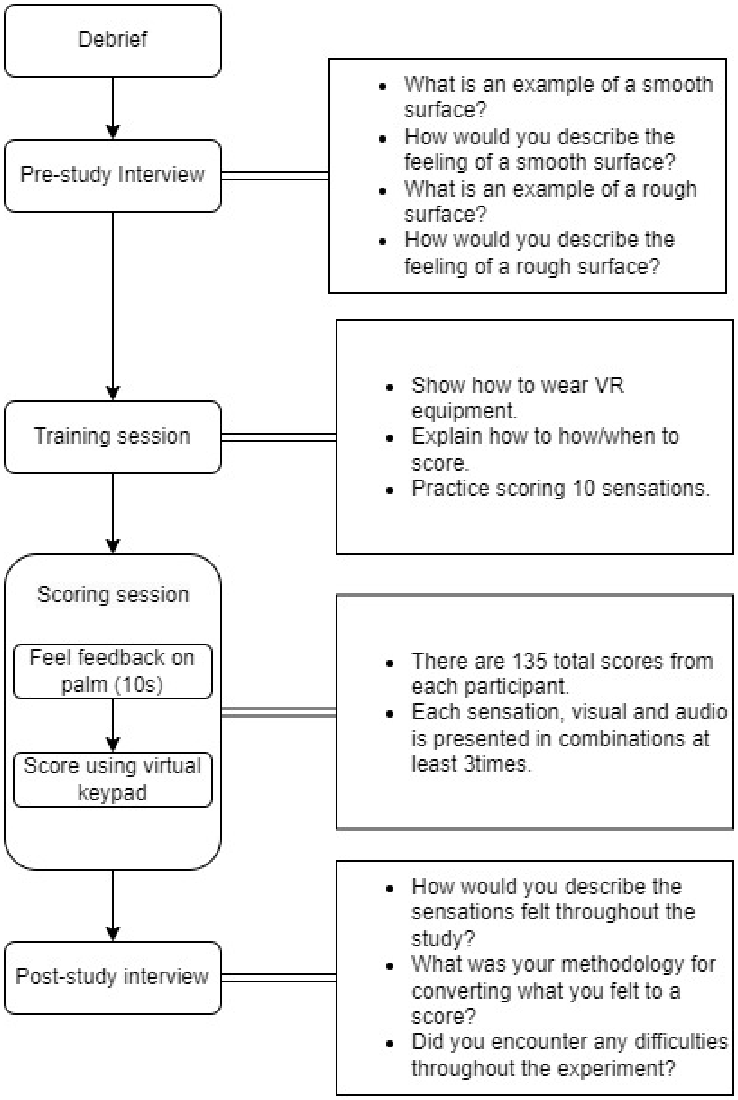


Figure 5.7: A temporal representation of 1 second recordings of a finger traversing over a sandpaper with grit value of 1000.

Procedure



- What is an example of a smooth surface?
- How would you describe the feeling of a smooth surface?
- What is an example of a rough surface?
- How would you describe the feeling of a rough surface?

- Show how to wear VR equipment.
- Explain how to how/when to score.
- Practice scoring 10 sensations.

- There are 135 total scores from each participant.
- Each sensation, visual and audio is presented in combinations at least 3times.

- How would you describe the sensations felt throughout the study?
- What was your methodology for converting what you felt to a score?
- Did you encounter any difficulties throughout the experiment?

Figure 5.8: A diagram depicting the procedure of the study.

The participant is seated on a desk where he faces the Valve Index virtual reality headset in the middle of the desk, a 20cm cube which will be used as a stand for his right arm and finally in front of the cube the UHEV1. The participant is debriefed on what stages the study session is comprised of.

First, there will be a warm-up audio-recorded, semi-structured interview where the participant will answer a few basic questions. The questions are: What is an example of a smooth surface? How would you describe the feeling of a smooth surface? What is an example of a rough surface? How would you describe the feeling of a rough surface? This initial interview is used for two reasons: a) to Bootstrap the participants' haptic vocabulary and b) to inform the researcher of what is the initial participants' opinion regarding roughness.

Following that, the participant is demonstrated how to wear the virtual reality headset, what he is expected to feel on his right palm, and how and when to enter a roughness score. Following, that the participant will attend a training session, where he will feel, hear and see 10 sensations as a part of a training session. After ending the training session, the participant is seated and left to complete this scoring session. During the session, the participant will feel for 10 seconds of ultrasound haptic feedback on his right palm. During this time in the virtual area, there might be present visual models of papers and audio cues of varying roughness. Following the end of the 10 seconds, the participant is presented with a virtual keypad that allows him to enter a roughness score. When the participant scores the final combination, a red label opposite of him informs him that the stage has ended.

Finally, after the scoring stage, the participant will partake in a semi-structured, audio-recorded interview with the lead researcher. The following are the leading questions: "How would you describe the sensations felt throughout the study?", "What was your methodology for converting what you felt to a score?", "Did you encounter any difficulties throughout the experiment?". A visual for the procedure is shown in figure 5.8

Participants

The study had 12 participants enlisted. The participants were composed mostly of healthy young adults (aged between 18-35) and were primarily members of the staff or students from the University of Glasgow. For each one-hour session, every participant was given a £10 Amazon gift card for full completion of the session.

5.3.3 Results

The data first went through a standardisation process, since this was a magnitude estimation study, this enforces a mean of 0 and an SD = 1 over the dataset. In order to assess the normality of the data, the Shapiro-Wilk test was conducted. The Shapiro-Wilk test evaluates whether a sample comes from a normally distributed population. The results indicated a test statistic W = 0.59, with a p-value < 0.05, for a sample size of n = 1350. Since the p-value is exceedingly small, we reject the null hypothesis of normality. This indicates that the sample data significantly deviates from a normal distribution. Therefore, to test the data a non-parametric Kruskal-Wallis test is performed for each IV.

Mid-air patterns

The mid-air pattern dataset descriptive analytics are presented in table 5.3. The Kruskal-Wallis test to evaluate the differences in roughness estimation scores across the five different mid-air pattern conditions indicated a statistically significant difference in roughness estimation scores among the groups, $H(4) = 317.03$, $p < 2.2 \times 10^{-16}$. A boxplot between roughness scores and patterns is shown in figure 5.9. Since Kruskal-Wallis reported statistically significant, then at least one of the IVs reported statistically significant differences, but to identify which groups of the data differ a post-hoc Nemenyi test was performed for each IV group. The results of the Nemenyi test are presented in Table 5.4. The Nemenyi post-hoc test indicated that significant differences were found between multiple pairs of mid-air patterns, particularly between circles and other patterns such as dots, horizontal lines, and vertical lines.

Table 5.3: Descriptive Statistics for Roughness Scores by Pattern

Pattern	**Median Roughness Score**	**Q1 (25th Percentile)**	**Q3 (75th Percentile)**
Circles	0.00728	-0.197	0.415
Square	-0.400	-0.604	-0.0997
Horizontal Lines	-0.461	-0.604	-0.197
Assymetrical	0.0990	-0.197	0.517
Vertical Lines	-0.400	-0.563	-0.0946

Notes: This table presents the descriptive statistics for roughness scores across different patterns. The median roughness score represents the middle value of the scores for each pattern. The first quartile (Q1) indicates the 25th percentile, while the third quartile (Q3) indicates the 75th percentile. These statistics provide a summary of the central tendency and variability of roughness scores for each pattern.

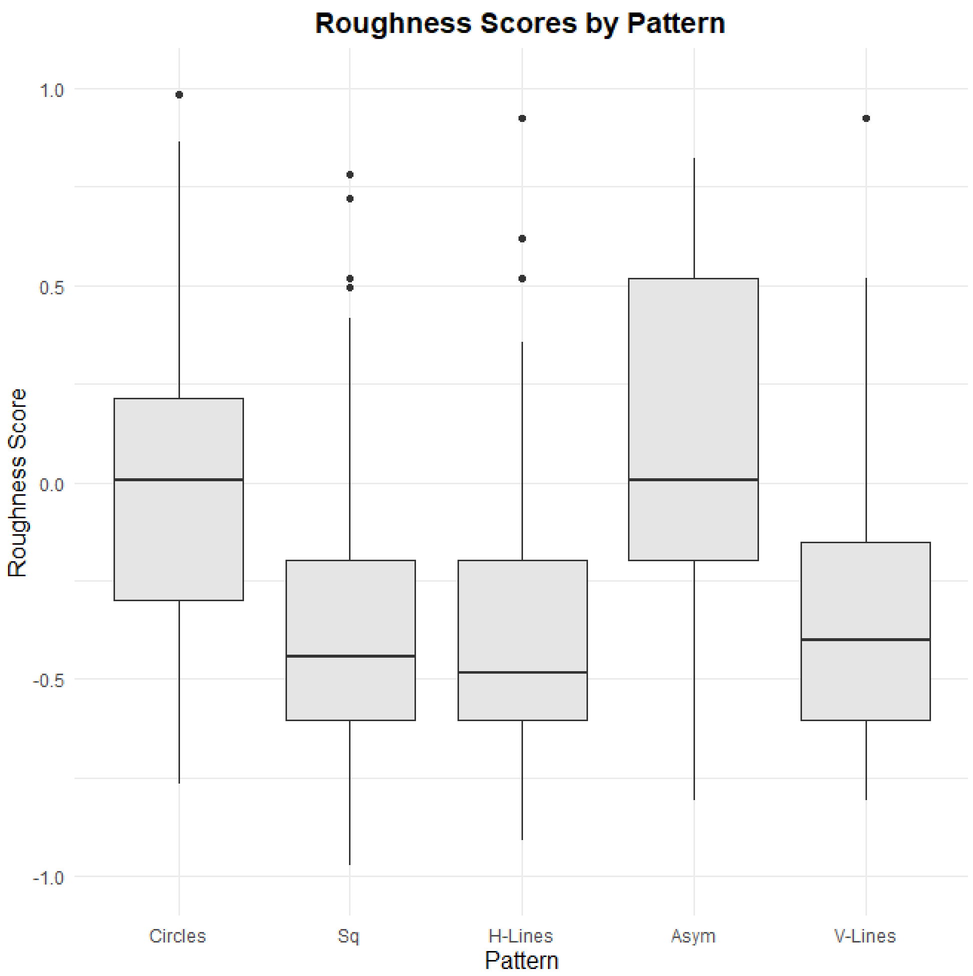


Figure 5.9: A boxplot representing the roughness scores on the y-axis and the associated pattern on the x-axis.

Table 5.4: Nemenyi post-hoc test results for mid-air patterns

Comparison	**Mean Rank Difference**	**p-value**
Square vs. Concentric Circles	-451.65	$< 2 \times 10^{-16***}$
Horizontal Lines vs. Concentric Circles	-520.22	$< 2 \times 10^{-16***}$
Assymetric vs. Concentric Circles	62.59	0.3361
Vertical Lines vs. Concentric Circles	-416.11	$< 2 \times 10^{-16***}$
Horizontal Lines vs. Square	-68.57	0.2452
Assymetric vs. Square	514.24	$< 2 \times 10^{-16***}$
Vertical Lines vs. Square	35.54	0.8273
Assymetric vs. Horizontal Lines	582.81	$< 2 \times 10^{-16***}$
Vertical Lines vs. Horizontal Lines	104.11	0.0164^{*}
Vertical Lines vs. Assymetric	-478.70	$< 2 \times 10^{-16***}$

Note: $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $\alpha = 0.05$

Visual modalities

The visual dataset descriptive analytics are presented in table 5.5. The Kruskal-Wallis test was also conducted to evaluate the differences in roughness estimation scores across the three visual modality conditions (smooth paper, semi-rough paper, and rough paper). The results indicated no statistically significant difference in roughness estimation scores among the groups, $H(2) = 3.5371$, $p = 0.1706$. Figure 5.10 shows a boxplot for roughness scores and visuals. Despite the non-significant overall result, a Nemenyi post-hoc test was performed for completeness. The results are presented in Table 5.6. The Nemenyi post-hoc test results indicated no significant differences between the visual modality groups. This suggests that the different visual modalities (smooth, semi-rough, and rough) did not significantly affect roughness perception.

Table 5.5: Descriptive Statistics for Roughness Scores by Visual Condition

Visual Condition	**Median Roughness Score**	**Q1 (25th Percentile)**	**Q3 (75th Percentile)**
Irregular Visual	-0.197	-0.502	0.109
Rough Visual	-0.197	-0.502	0.0633
Smooth Visual	-0.197	-0.543	0.0277

Notes: This table presents the descriptive statistics for roughness scores across different visual conditions. The median roughness score represents the middle value of the scores for each visual condition. The first quartile (Q1) indicates the 25th percentile, while the third quartile (Q3) indicates the 75th percentile. These statistics provide a summary of the central tendency and variability of roughness scores for each visual condition.

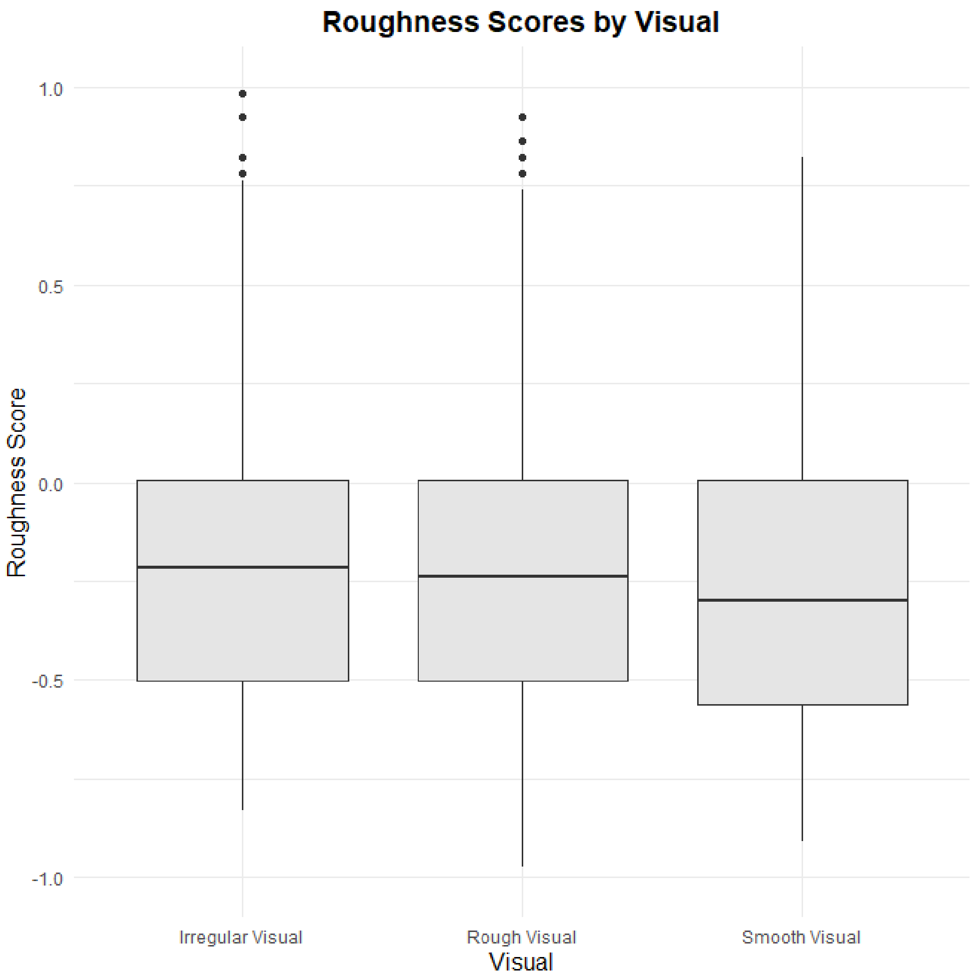


Figure 5.10: A boxplot representing the roughness scores on the y-axis and the associated visual on the x-axis.

Table 5.6: Nemenyi post-hoc test results for visual modalities

Comparison	**Mean Rank Difference**	**p-value**
Rough Visual vs. Irregular Visual	-11.83	0.8921
Smooth Visual vs. Irregular Visual	-47.19	0.1644
Smooth Visual vs. Rough Visual	-35.36	0.3618

Note: $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $\alpha = 0.05$

Audio modalities

The visual dataset descriptive analytics are presented in table 5.7. A Kruskal-Wallis test was also conducted to evaluate the differences in roughness estimation scores across the three audio modality conditions (smooth audio, semi-rough audio, and rough audio). The results indicated no statistically significant difference in roughness estimation scores among the groups, $H(2) = 1.8785$, $p = 0.3909$. Figure 5.11 shows a boxplot for roughness scores and audio. A Nemenyi post-hoc test was performed for completeness. The results are presented in Table 5.8. The

Nemenyi post-hoc test results indicated no significant differences between the audio modality groups. This suggests that the different audio modalities (smooth, semi-rough, and rough) did not significantly affect roughness perception.

Table 5.7: Descriptive Statistics for Roughness Scores by Audio Condition

Audio Condition	**Median**	**Q1 (25th Percentile)**	**Q3 (75th Percentile)**
Irregular Audio	-0.197	-0.523	0.00728
Rough Audio	-0.197	-0.502	0.104
Smooth Audio	-0.197	-0.502	0.0837

Notes: This table presents the descriptive statistics for roughness scores across different audio conditions. The mean roughness score represents the average value of the scores for each audio condition. The standard deviation (SD) indicates the amount of variation in the scores. The median roughness score represents the middle value of the scores. The first quartile (Q1) indicates the 25th percentile, while the third quartile (Q3) indicates the 75th percentile. These statistics provide a summary of the central tendency and variability of roughness scores for each audio condition.

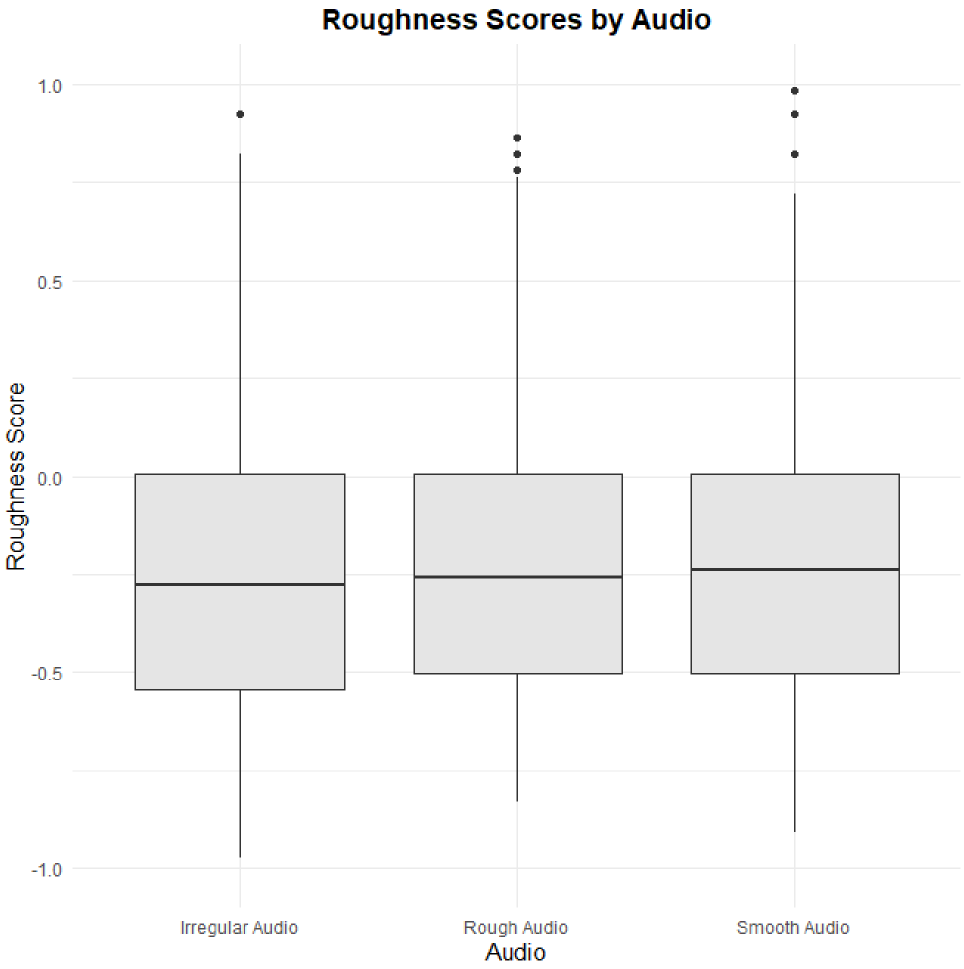


Figure 5.11: A boxplot representing the roughness scores on the y-axis and the associated audio on the x-axis.

Table 5.8: Nemenyi post-hoc test results for audio modalities

Comparison	**Mean Rank Difference**	**p-value**
Rough Audio vs. Irregular Audio	20.38	0.7128
Smooth Audio vs. Irregular Audio	24.65	0.6096
Smooth Audio vs. Rough Audio	4.27	0.9852

Note: $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $\alpha = 0.05$

Qualitative Data

From the pre-experiment interview, a list was collected of materials that participants thought were either smooth or rough and the attributes that they thought played a role in feeling smooth or rough. Table 5.9 shows the list of materials and their count of mentions and table 5.10 shows the list of attributes.

Rough	Mentions	Smooth	Mentions
sandpaper	4	fabric	2
ground/floor	4	stressball	1
carpet	2	glass	1
rock	1	plastic	1
wood	1	skin	1
blackboard	1	water	1
pavement	1	building	1
table	1	balloon	1
wall	1	table	1
brick	1	slab	1

Table 5.9: Table listing rough and smooth materials expressed from the study's participants, along with a count of how many times they were mentioned.

Rough	Smooth
ridges	flat
inflexible	pliable
grainy	lack of graininess
tingly	unchanging sensation
rigid	soft
unpleasant	pleasant
hard	lack of pressure
uneven	even
needles	easy to slide
full	

Table 5.10: Table listing rough and smooth material attributes by the study's participants.

From the post-study interviews, the main goal was to identify the methodology with which the participants scored the tactile patterns and to unveil how the differences in the audio and visual modalities impact their decision. Most participants explained that they rely on tactile feedback as a primary source of information and disregarded the changes in visuals and audio. The exceptions to the above were P1 who said that they used tactile as the primary source and then used the visuals as an adjustment tool while ignoring sounds, and P3, P4 who instead used sound to help with associating the sensation to a roughness score. P1 also explained that the mismatch between what they were seeing and what they were feeling caused issues with scoring. P3 explained that the main method of scoring was by how fast the sensations travelled on the palm, which was later enriched by the sound. P5 used the idea of pinches to quantify a score. Users P6, P7, and P9 explained that they used their instincts to score the roughness and did not have any methodology. P9 also explained that the total area affected on the palm was a secondary criterion. Additionally, P9 also explained that they tried to imagine what surface could the sensation that they felt was before scoring. P8 explained that the intensity of the tactile sensations was the only criterion for scoring. Most participants found the audio to be a distraction when scoring even though they could differentiate between the different rough sounds.

5.3.4 Discussion

> **H1** Increased roughness scores will be observed when rougher-looking visual modalities are shown due to the rougher visuals addressing textural information deficiencies.
>
> **H2** Increased roughness score will be observed when rougher-sounding audio cues are triggered because the audio will provide roughness information.

The focus of this study tried to answer research questions **RQ3** and **RQ4** by investigating the effects of audio and visual modalities when they are present with ultrasound-generated mid-air textures. Based on the results above it is clear that visual and audio modalities did not show any significant impact on the roughness scores of the mid-air patterns. This is also evident in the post-study interview results, most participants disregarded the visual and audible modalities or found them to be distracting.

The results match previous studies in the field, both sound and visuals play a minor role in roughness discrimination. However, in this study, it is clear that there was no impact at all. It is fortunate, however, to see that the pattern scores are almost identical to the previous mid-air pattern study (Study 3), the different patterns indeed produced different roughness scores. It is evident that focusing on producing better and more varied patterns is a path worth pursuing when trying to create the sensation of varying roughness in a person.

5.3.5 Limitations

I believe there was a dissonance between the participants' expectations of what they initially thought is rough and the type of roughness they felt in actuality. The visuals were generated in the form of a paper which varied in roughness, based on the height of their peaks and their inter-element spacing, however, it is clear that not all the participants had that visual as an idea. Table 5.9 shows that sandpaper is indeed a common rough surface, but a lot of the participants had other objects or surfaces visualised. Exploring this in the future I would suggest instead of taking one visual and manipulating it to be rougher, it would be more beneficial to vary the type of visual, e.g. prepare visuals of a box of rocks, a carpet or a plane filled with rocks. Given the results in table 5.10 I would even suggest making the visuals interactable, being able to be manipulated to show pliability, or introducing effects to show graininess. The same concept can be repeated for audio modalities, trying to simulate the sound of a palm over sandpaper is a limiting idea since that is just one audio cue, that a participant might have never heard in their life.

5.3.6 Summary

This study attempted to combine mid-air patterns from Study 3 with audio, visual and audiovisual modalities in an attempt to understand how high-fidelity visuals and audio cues can affect the roughness scores of mid-air patterns. To achieve that high-quality visual models and intricate audio cues were generated to achieve that goal. This study was essential to answer the fourth research question **RQ3** and **RQ4**.

> **RQ4** How do audio-visual modalities improve roughness perception of ultrasound-generated sensations?

Audiovisual modalities, unfortunately, did not have any impact on the roughness scores, as all of the statistical results were found statistically insignificant. Unlike Study 4, which has shown some performance increase in discrimination rates, audiovisual modalities had no effect in this one.

> **RQ3** Does the use of basic ultrasound haptic patterns such as circles, lines, and dot arrays accurately simulate textures of varying levels of roughness?

The similarity of the results of the mid-air patterns with Study 3 suggests that even if visual or audio cues did not have an effect, the patterns themselves were enough to properly convey a standard roughness sensation. Therefore, for **RQ3** it can be said that mid-air patterns are a viable option that should be explored further to identify which exact properties were responsible for conveying the roughness scores.

Chapter 6

Conclusions

This thesis delved into the innovative use of ultrasound haptics to simulate tactile roughness, advancing at the same time the understanding of haptic technologies, virtual environments and haptics. Through a series of detailed experiments, this work explored the potential of ultrasound haptics to create nuanced sensations of texture and roughness without physical contact. Central to these investigations was the examination of various parameters such as hand traversal speed, focal point numbers, movement direction, and inter-element spacing, and how they can be manipulated to enhance the perception of tactile qualities in a non-tangible format.

Furthermore, this research extended into the realm of multimodal interactions, incorporating audio and visual stimuli to assess their impact on the tactile experience. The integration of these modalities aimed to understand how they can complement or detract from the haptic feedback, providing a richer sensory experience or potentially introducing sensory conflicts.

The conclusions that will be drawn from this study not only highlight the capabilities and limitations of ultrasound haptics but will also suggest directions for future research. This chapter aims to combine these findings, offering insights into the practical applications and theoretical implications of enhancing virtual reality systems with sophisticated haptic feedback.

To begin, the initial research questions will be articulated and elaborated upon, detailing whether resolutions were reached and discussing their broader implications. Subsequently, a section on contributions will enumerate the significant advancements this study has made to the field, referencing specific results and experimental inquiries. Lastly, an outline of potential avenues for future research along with a critical examination of any constraints that may have influenced the outcomes will be provided.

6.1 Research Questions

6.1.1 RQ1

> **RQ1:** How does the Hand Traversal Speed of an ultrasound focal point improve the discrimination of realistic textured surfaces?

RQ1 tries to determine the effectiveness of a focal point's hand traversal speed at texture discrimination. The literature explains that hand traversal speed enhances the perceived tactile perception. In this thesis, the hand traversal speed parameter was studied in the form of a focal point's speed actuating over a participant's palm. The aforementioned parameter was studied in Study 1, and the results were used to establish Study 4.

Study 1 prepared four textured surfaces that were actuated using ultrasound haptics to a participant's palm. The four textured surfaces could have two different hand traversal speeds, therefore, in total, creating eight different surfaces. The results of the study suggested differences in the effectiveness of hand traversal speed on texture discrimination, as it affected each textured surface differently. Contrasting the two differing hand traversal speeds, there is a noticeable shift of the smoother textured surfaces (Flat and Checkerboard) in being better discriminated against when presented with the higher hand traversal speed of 64Hz.

6.1.2 RQ2

> **RQ2:** How do changes in speed, focal point number, movement direction, and inter-element spacing affect perceived roughness scores?

RQ3 intends to provide an understanding of how parameters such as speed, focal point number, movement direction and inter-element spacing enhance a subject's perception of texture roughness when integrated into ultrasound haptics. Previous literature investigating those parameters has found that in traditional haptic modalities involving solid objects, these parameters were successful at modulating the effectiveness of conveying material roughness to subjects. This thesis investigated the effect of these parameters in Study 2.

Study 2 investigated in isolation the aforementioned parameters by using a series of focal points projected onto a subject's palm. From the four parameters, speed, focal point number, and inter-element spacing were found to be able to convey varying levels of perceived roughness. The thematic analysis in Study 2 concluded with the realisation that a subject expects roughness to be mediated through the means of the sensation of movement and the actuation of large enough areas on their palm.

Speed, focal point number, and inter-element spacing can help convey material roughness perception. Also, the sensation of movement and area of actuation can be indicators of roughness.

6.1.3 RQ3

> **RQ3:** Does the use of basic ultrasound haptic patterns such as circles, lines, and dot arrays accurately simulate textures of varying levels of roughness?

RQ3 attempts to understand the effectiveness of haptic patterns as a way to convey the perception of roughness. In literature, simple patterns were created by using resistant patches that resisted the movement of a finger over them. Those simple patterns came in the form of vertical and horizontal lines, concentric circles and dot arrays. This thesis investigated a recreation of those patterns but generated them using ultrasound instead. Two studies participated in answering RQ3, Study 3 and Study 5.

Study 3 used some of the findings from Study 2 to effectively formulate the mid-air patterns design. The aim was to measure the perceived roughness score of the different pattern designs. The study concluded with most patterns having a significantly unique roughness score. The speed magnitude of the focal point speed was also studied, which decreased the roughness score of most of the affected patterns by increasing it.

Study 5 studied how mid-air patterns are affected by visual and audio modalities. The aim was to study how the audiovisual modalities can affect roughness score compared to Study 3. Neither audio nor visual modalities managed to affect the perceived roughness of the participants of Study 5.

In summary, patterns such as circles, lines and dot arrays can successfully convey roughness to a user.

6.1.4 RQ4

> **RQ4:** How do audio-visual modalities improve roughness perception of ultrasound-generated sensations?

RQ4 intended to study the effects of audio and visual modalities on ultrasound-generated textures, specifically, how they can improve the roughness perception. The literature suggested that visuals could affect haptic perception by employing the participants' bias about the properties of an object or texture, and even though visuals do not encompass a substantial weight in haptic perception, they still have a secondary measured effect. Two studies were conducted to answer this research question: Study 4 and Study 5.

Study 4 tested the use of audiovisual modalities with ultrasound-generated textured surfaces that were created in Study 1. By generating the visual and audio models that depicted smooth, semi-rough and rough versions, the study investigated the effect of the audiovisual modalities on the aforementioned textured surfaces and concluded that the visual modality was responsible for improving the texture discrimination of two out of the three textured surfaces. The study also found that audio instead had a diminishing factor to texture discrimination and that the combination of audio and visual sat between the visual and audio.

Study 5, similar to Study 4, tested the effects of audiovisual modalities in mid-air patterns, simple patterns of actuated ultrasound haptics generated for Study 3. This study investigated how audio and visual modality affected the roughness scores of different mid-air patterns. The results concluded that neither audio nor visuals affected the roughness scores and that roughness scores are proportionally unaffected from Study 3.

In summation, audio and visual modalities affect ultrasound-generated textured surfaces, where visual models seem to aid the discrimination of some textures, whereas audio impedes the discrimination. For mid-air patterns, no effect has been recorded.

6.2 Contributions

First, there is a gap in the literature concerning the use of roughness-conveying parameters in ultrasound haptics, explicitly speed, focal point number, movement direction and inter-element spacing. This thesis contributes to studying traditionally roughness-mediating parameters in ultrasound haptics and evaluating their ability to convey roughness with the nonexistence of solid matter. Two studies (1 and 2) have been performed, and significant results have been recorded. In these studies, it was concluded that Hand Traversal Frequency had varying effects on the different textures. Haptic Acuity predicted better results for subjects with a better score. Speed, focal point number, and interelement spacing have shown the ability to modulate perceived roughness, with speed being the most influential. Finally, movement direction could not modulate the perception of roughness, unlike what was expected from the literature (where actuating different parts of the palm is expected to provide varying levels of perceived roughness).

Secondly, the work in this thesis appends to the research of patterned textures by using previously used patterns but generating them using ultrasound haptics. The contributions provide significant results in the form of different textures promoting different roughness sensations, which can be used as a benchmark in future studies in the field. Studies 3 and 5 contributed to these results.

Thirdly, the thesis builds on top of previous literature by studying the effectiveness of visual and audio modalities in modulating roughness perception. Specifically, the contributions are made by using realistically made mid-air surfaces and mid-air patterns. The results make apparent the intricacies that need to be aware of when attempting to convey roughness through visuals and audio in ultrasound haptics.

Lastly, this thesis adds to the literature two thematic analyses (Studies 2 and 3), which focused on understanding a subject's thought process when evaluating the roughness perception of mid-air actuation. The byproducts of the thematic analyses also provide sets of roughness conveying vocabularies that can aid future research in the roughness mediating field.

6.3 Future Work and Limitations

A future work worth pursuing is the study of the actuation frequency of the focal points regarding roughness perception. Actuation frequency is - similar to a signal frequency - the time it takes for the highest intensity to reduce to the lowest and back to the highest. Literature does mention that different vibratory frequencies are responsible for stimulating the different mechanoreceptors in a human's palm. Each mechanoreceptor is capable of signalling other sensations to the person. The ultrasound haptics technology, by design, is capable of modulating the actuation frequency of a focal point; however, that ability is used to maximise the intensity of the perceived tactile actuation. This study was theorised but descoped due to timing constraints. However, it can provide insight into the effectiveness of ultrasound haptics to actuate different mechanoreceptors precisely, and it can also provide feedback on any design complications that can become apparent with varying actuating frequencies.

Another piece of future work could be considered in generating more mid-air patterns. Mid-air patterns were the most promising result in this thesis, and they could consistently convey varying roughness sensations. It would be beneficial to expand the list of mid-air patterns to generate a spectrum of low and high roughness patterns to aid future work in the field of roughness perception.

Furthermore, the thesis lacked any longitudinal studies. Many of the technologies, be it ultrasound haptics or VR technologies are still quite new for most subjects. It would be beneficial to investigate how prolonged exposure over time could impact roughness perception and the overall experience.

A final future work that should be considered is replicating roughness-conveying effects. In the thematic analyses, subjects mentioned the sensation of tingling, sliding, and pleasantness/ unpleasantness. Future work should work on understanding the factors for generating and modulating those sensations since they have been found multiple times in the studies of this thesis as contributing factors of roughness/smoothness.

Study 4 introduced the first iteration of the visual and audio modalities. The visual textures resembled varying roughness levels of a blank paper, and the audio modalities had varying amplitude levels. Study 5 built upon those and updated the visuals with more noticeable irregularities, and the audio was analysed more in-depth to modulate audio perception in specific frequencies, mimicking the way real sounds do. However, both modalities have been shown to not be very good at modulating roughness perception, contrary to previous literature that used older technologies (e.g. monitors instead of VR headsets). A limitation of this thesis is that those modalities could have been better designed. The visuals were high fidelity but not realistic. Audio modalities clearly produced variations of white noise as expected from such an interaction, but participants were introduced to it before performing the experiment. It was left up to chance for the participant to recall what an interaction of a palm traversing a paper sounds like. Future work should keep in mind that interactions such as feeling something, recalling how it looks and how it sounds can be a variable that can skew the data in the studies of this thesis. It would be beneficial to introduce the subjects to how the visuals look and sound in reality before transferring them to a virtual world. Finally, an important limitation that spun across all studies was the lack of reporting the participants' gender. The two biological genders have differences in the way they perceive tactile feedback, e.g. for women, the combination of touch and smell can change how pleasant both the touch and the smell feel [155]. It should be noted for future work that demographic data is important to be collected.

An important limitation that should definitely be addressed is the lack of demographic data. All of the studies lacked any collection of demographic data. The most important is the gender of the participants, which is important as the different genders can have different sensitivities to tactile perception. An independent group study covering an equal number of participants from both genders may shed light on how different persons discriminate or perceive differently textured surfaces using ultrasound.

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