Human Factors Considerations for Ultrasound Induced Mid-Air Haptic Feedback

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Abstract

The engineering design process can be complex and often involves reiteration of design activities in order to improve outcomes. Traditionally, the design process consists of many physical elements, for example, clay/foam modelling and more recently Additive Manufacturing (AM), with an iterative cycle of user testing of these physical prototypes. The time associated with creating physical prototypes can lengthen the time it takes to develop one product, and thus, comes at a burdensome financial and labour cost. Due to the aforementioned constraints of the conventional design process, more research is being conducted into applications of Virtual Reality (VR) to complement stages of the design process that would otherwise take and cost a significant amount of time and money. VR enables users to create 3D virtual designs and prototypes for evaluation, thus facilitating the rapid correction of design and usability issues. However, VR is not without its pitfalls, for example, it often only facilitates an audio-visual simulation, thus hindering evaluation of the tactile element of design, which is critical to the success of many products.

This issue already has a wide body of research associated with it, which explores applications of haptic (tactile) feedback to VR to create a more realistic and accurate virtual experience. However, current haptic technologies can be expensive, cumbersome, hard to integrate with existing design tools, and have limited sensorial output (for example, vibrotactile feedback). Ultrasound Haptic Feedback (UsHF) appears to be a promising technology that offers affordable, unencumbered, integrable and versatile use. The technology achieves this by using ultrasound to create mid-air haptic feedback which users can feel without being attached to a device. However, due to the novel nature of the technology, there is little to no literature dedicated to investigating how users perceive and interpret UsHF stimuli, and how their perception affects the user experience.

The research presented in this thesis concerns the human factors of UsHF for engineering design applications. The PhD was borne out of interest from Ultraleap (previously Ultrahaptics), an SME technology developer, on how their mid-air haptic feedback device could be used within the field of engineering. Six studies (five experimental and one qualitative) were conducted in order to explore the human factors of UsHF, with a view of understanding its viability for use in engineering design. This was achieved by exploring the tactile ability of users in mid-air object size discrimination, absolute tactile thresholds, perception of intensity differences, and normalisation of UsHF intensity. These measures were also tested against individual differences in age, gender and fingertip/hand size during the early stages, with latter stages focussing on the same measures when UsHF was compared to 2D multimodal and physical environments.

The findings demonstrated no evidence of individual differences in UsHF tactile acuity and perception of UsHF stimuli. However, the results did highlight clear limitations in object size discrimination and absolute tactile thresholds. Interestingly, the results also demonstrated psychophysical variation in the perception of UsHF intensity differences, with intensity differences having a significant effect on how object size is perceived. Comparisons between multimodal UsHF and physical size discrimination were also conducted and found size discrimination accuracy of physical objects to be better than visuo-haptic (UsHF) size discrimination. Qualitative studies revealed an optimistic attitude towards VR for engineering design applications, particularly within the design, review, and prototyping stages, with many suggesting the addition of haptic feedback could be beneficial to the process.

This thesis offers a novel contribution to the field of human factors for mid-air haptics, and in particular for the use of this technology as part of the engineering design process. The results indicate that UsHF in its current state could not offer a replacement for all physical prototypes within the design process; however, UsHF may still have a place in the virtual design process where haptic feedback is required but is less reliant on the accurate portrayal of virtual objects, for example, during early stage evaluations supplemented by later physical prototypes, simply to indicate contact with virtual objects, or when sharing designs with stakeholders and multidisciplinary teams.

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Chapter 1: Introduction

1.1. Background and Research Context

This PhD was borne out of interest from the industry partner, Ultraleap (previously Ultrahaptics) in the potential for their ultrasound haptic technology to be applied within the engineering sector, specifically for virtual engineering design. The technology uses ultrasound transducers which when emitting the correct frequency, stimulate the receptors in the hands associated with tactile perception. In turn, the user experiences invisible but ‘touchable’ versions of virtual objects, which has the potential to revolutionise interaction with VR.

As a relatively new company with a novel technology, the research phase was understood to be paramount before pursuing applications outside of their already growing portfolio in which they have applied their technology to convert public touchscreens to touchless displays with haptic feedback, a particularly relevant development in the COVID-19 era. They have also implemented their device within in-car gesture displays to alleviate some of the issues encountered with lack of feedback during cognitively and visually demanding tasks such as driving.

When this PhD was conceived, the existing literature and indeed the gaps within it were of utmost importance. From a review of existing publications (Chapter 2), several observations were made. Initially, it was apparent that there was a copious amount of experimental literature on VR over the course of the last five decades within a broad range of applications, from surgical training to engineering. The caveat to the existing VR literature is that it often only considers audio-visual VR and does not explore the incorporation of feedback for any other senses, particularly tactile feedback. Though there is literature exploring the use of tactile/haptic feedback in VR, it is not as common and often has an emphasis on technologies that are not widely used and have limited use cases, such as haptic gloves and exoskeletons. The literature on haptics also does not consider the human factors issues surrounding the feedback methods and how these may affect interaction with such devices.

Due to the novel nature of mid-air haptics, the current literature does not adequately explore some of the intricate detail required to understand whether current knowledge about the sense of touch can be applied to this new technology. This means it is unclear whether findings from even other haptic devices can be translated in the same way to mid-air haptic feedback. Thus, research into mid-air haptics, in this instance UsHF, is required to understand how users will perceive ultrasound haptic sensations. Furthermore, it is imperative that these findings be transferable to VR engineering design applications.

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1.2. The Engineering Design Process

Though the engineering design process is not the primary focus of this PhD, it is relevant to the justification of the work, and thus will be summarised in this section. The ‘engineering design process’ is a broad term which refers to the stages of design, from conception to fruition. The process is a relatively universal term and can be summarised in several stages. According to Haike and Shahin (2011), these stages consist of establishing an objective and criteria, synthesis, analysis, construction, testing and evaluation. These stages are often extended to include more precise stage definitions, but for the purposes of this research, the aforementioned design increments are sufficient.

1.2.1. Objectives and Criteria

The initial stage of the design process encompasses many components and tasks that eventually lead to a solution to the given problem that a product is being designed for. Initially it is important to identify customer needs, conduct market analysis and define goals, which is usually done via a requirements process. This process will typically have hundreds or even thousands of elements specifying the attributes of the end product. It can be noted that this is one of the most important stages of the design process as it can negatively impact the subsequent design phases if neglected (Halbleib, 2004).

1.2.2. Synthesis

From the requirements process is the development, or synthesis of the solution, which establishes product functions and conceptualises the solution. In understanding and setting out product functions, it allows for alternative approaches to be implemented for the benefit of the primary goal. Product conceptualisation builds on the principle of exploring alternative solutions, as this stage encourages the generation of new ideas, and determines how well those ideas fit with the previous requirements stage, as well as the end goal. Finally, a decision is made on which design or concept should be adopted and progressed to the following stages (Halbleib, 2004).

1.2.3. Analysis

At this stage previous concepts from the synthesis stage are analysed, tested, and honed to facilitate the constraints of the manufacturing process. This stage also ensures the product’s predicted usefulness by contrasting the product thus far to the initial requirements and goals. Any changes at this stage undergo analysis again to ensure the changes improve the design, also known as optimisation (Halbleib, 2004).

1.2.4. Construction, Testing and Evaluation

After analysis and the final design is chosen, it is constructed and verified against the previous stages to ensure it meets the design criteria. During this stage, the durability and performance of the mock-up, model and/or prototype are tested. If all requirements and goals are satisfied, the final prototyped product is marketed.

1.3. Defining the Problem

The engineering design process can be a time and cost intensive process, as such, industry is always looking for methods and technologies to improve efficiency and cost savings without compromising the final product (e.g., Mujber, Szecsi, & Hashmi, 2004). Indeed, there is always an impetus to improve the finished product, which means it is imperative that the quest to save time and money does not have a negative impact on designs. This is to not only to maximise profit, but also to benefit the user experience of the product that is eventually marketed. Indeed, Additive Manufacturing (AM), a process by which parts can be constructed through successive addition of layers, seeks to alleviate some of the environmental, economic and time burdens of the design process by facilitating rapid and frequent prototypes that can be made during the design process. This in turn allows early design issues to be identified and rectified, benefits that are often cited in the literature, particularly when compared to conventional machining and casting methods (Mami, Reveret, Fallaha, & Margini, 2017). However, naturally there are still sustainability and cost issues associated with AM, not only due not only to the waste from multiple design iterations and initial cost of equipment, but also energy consumption associated with the process. The benefits and some of the drawbacks associated with AM were corroborated by George (name replaced for anonymity), an industry-based additive manufacturing specialist who gave their insight at the beginning of this PhD. They stated:

> *"We rely heavily on additive manufacturing and often create multiple iterations of small components. This helps ensure that our designs are right before they are manufactured. However, because of the scale of the company, the 3D prototypes are often shipped between different company locations and teams before ultimately being disposed of".*

Though this commentary gives insight into how AM can be used to rapidly manufacture multiple iterations of a design, it also highlights the logistical and waste issues with utilising AM on a large scale. In light of the aforementioned problems with AM, in order to continue the trend of time and money savings during the product development process, industry has explored other avenues that have the potential to save time, money and material whilst simultaneously being able to port ideas to different locations and teams effortlessly (e.g., Kovar, et al., 2016; Wolfartsberger, 2019).

Virtual Reality (VR) is increasingly becoming commonplace in design settings for several reasons. Firstly, high quality, reasonably priced VR became significantly cheaper in recent years with the introduction of Head Mounted Displays (HMDs) such as the Oculus Rift and the HTC Vive (Stuchlikova, Kosa, Benko, & Juhasz, 2017). The benefit of low initial cost of VR equipment means that companies and indeed individuals are more likely to adopt the technology and begin development for their field, which results in growth in the number of potential applications. Secondly, VR opens up possibilities for the inclusion of team members that would have otherwise been excluded from the design process, for example, individuals who may not necessarily be trained to use Computer Aided Design (CAD) but have valuable knowledge of usability and ergonomics (Wolfartsberger, 2019), which in turn adds the potential for enhanced collaboration. Thirdly, as aforementioned, VR has the potential to save both time and money compared to physical prototyping, whilst addressing product lifecycle elements such as ergonomics, tooling design and maintenance (Seth, Vance, & Oliver, Virtual Reality for Assembly Methods in Prototyping: A Review, 2011).

Despite VR offering a number of benefits over new rapid prototyping solutions, there remains one salient issue, specifically, that VR does not offer the realism or fidelity of a physical object. Solutions to this issue in the form of haptic feedback show promise to alleviate some of VR's shortcomings by improving a number of elements of the VR experience, from realism and immersion (Azmandian, Hancock, Benko, Ofek, & Wilson, 2016), to practical improvements in reaching (Just, et al., 2016), grasping (Hinchet, Vechev, Shea, & Hilliges, 2018) and general object perception (Son & Park, 2018). However, despite some of the demonstrable benefits of haptic-VR, some researchers still believe there remains a lack of understanding of how haptics can influence user experience, stating the reason as being due to little knowledge of the theoretical foundations of the haptic experience (Kim & Schneider, 2020). Thus, it is important that foundational understanding of haptics, particularly emerging haptic technologies is at the epicentre of research in the field.

1.4. Research Aims and Objectives

Overall, the goal of this thesis can be summarised as to understand the nuances of Ultrasound Haptic feedback (UsHF) and explore subjective interpretation of mid-air objects whilst applying the knowledge gained to create recommendations for the implementation of UsHF within Virtual Reality (VR) for engineering design. However, this aim can be further segmented into a clearer direction for this thesis, as shown below.

1.4.1. Aims

1. **Investigate the human factors issues surrounding UsHF**

   As there is little demonstration of human-related issues surrounding UsHF in the literature, this aim was formulated in order to ensure that any findings throughout the PhD were valid and not as a result of underlying issues associated with interaction with the ultrasound device.

2. **Understand whether the presence of UsHF can be beneficial to interaction with virtual objects during engineering design applications**

   The literature (see Chapter 2) suggests the presence of haptic feedback can lead to improvements in interaction with virtual worlds. Before embarking on this thesis, it was unclear whether this understanding of haptics could be applied to UsHF, as it sets a different paradigm for tactile interfaces. Therefore, this research was conducted with the aim of understanding whether UsHF would offer benefits to multimodal interaction in engineering design applications.

3. **Determine whether the absence of kinaesthetic feedback is detrimental to user perception of mid-air objects**

   As UsHF creates mid-air sensations without physical characteristics normal objects embody, such as object hardness, resistance, temperature, and surface texture, it is unclear whether it can induce kinaesthesia, a process relevant during interaction with objects and which is reliant on perception of muscle and joint position. This research aimed to establish whether this deficiency is detrimental to overall user perception of virtual object characteristics.

4. **Explore whether UsHF objects can offer sufficient accuracy to replace physical objects in design tasks**

   On a similar line of inquiry as Aim 3, it remains unclear whether UsHF can serve as a suitable substitute for physical objects. This becomes particularly pertinent when considering applications wherein a combination of VR and UsHF could potentially replace, or at least compliment physical prototyping stages. Equally, this is relevant when considering whether UsHF should be used to replicate physical objects at all within the design process.

5. **Understand industry attitudes towards engineering related applications of VR and UsHF**

   A key consideration while implementing new technologies and solutions, is understanding not only how users intend to use it, but also attitudes, anticipated issues, predicted use habits and cases, and anticipated benefits. This aim was intended to be addressed via the use of both empirical enquiry with relevant, engineering-based users, as well as questioning potential industry users on a conceptual basis. This not only allows this thesis to make recommendations for the use of UsHF within industry, but also serves as a relevant information gathering practice helping create future research avenues.

The aims mentioned above are to be achieved via the satisfaction of six objectives which are also summarised below.

1.4.2. Objectives

1. **Investigate individual differences in UsHF object size perception**

   The literature (Chapter 2) indicated that individual differences, for example gender and hand size, contribute to differences in tactile ability. Therefore, experimental work was needed to determine whether these differences are present during use of UsHF, as this could have a negative impact on future implementations of the technology. Based on the literature, object size perception was determined to be an appropriate measure of tactile ability due to the importance of object accuracy in engineering design, and thus is a measure to be implemented throughout testing of UsHF.

2. **Investigate the populational differences in tactile thresholds when using UsHF**

   As the potential presence of individual differences was determined to be a limiting factor during the literature review, it was imperative that any other populational differences, for example age, gender, and hand size, in tactile ability be established early in the research cycle, thus avoiding distorted data in the future. This will be measured by employing a hybrid just noticeable different (JND) task to determine individual minimum detectable UsHF stimuli.

3. **Conduct experimental research to understand user perception of UsHF intensity**

   Initial use of the UsHF array indicated that intensity varied depending on the size of the mid-air object, even when displayed at the same intensity within the device software. This phenomenon, and how it was perceived by users needed to be investigated before continuing with application-specific studies. This will be achieved by manipulating UsHF intensity in order to understand how it affects perception of mid-air objects and whether varied intensity could potentially offer enough feedback for lower fidelity implementations of UsHF. Furthermore, it will be important to ensure all mid-air stimuli are perceived to be of the same intensity, thus this will be explored by attempting to normalise UsHF intensity.

4. **Study multimodal perception of virtual object size**

   As this thesis is concerned not only with UsHF, but UsHF within multimodal applications, it was deemed imperative that research on perception of UsHF objects be ported to multimodal applications as well. This in turn would give more real-world insight into perception of UsHF objects when used in VR for engineering design. Though it will not be possible to implement industry-specific scenarios, perception of visuo-haptic stimuli will be explored to understand how an often visual only task can be improved with the presence of UsHF

5. **Examine differences in size perception accuracy using UsHF with virtual objects compared to physical objects**

   As one of the original justifications for this research was to establish whether UsHF in a multimodal application could replace or at least, compliment traditionally physical engineering design tasks, it was imperative to establish whether that ambition is possible. During this PhD, it is not essential that the research into this objective is completely analogous of possible applications of multimodal UsHF, for example a complete visuo-haptic design environment, but it is important that research within this objective is as close as possible for findings to have external validity. In order to test this, physical objects will be 3D printed to mimic UsHF stimuli, after which users will engage in size discrimination tasks in which accuracy will be compared between the two mediums.

6. **Administer questionnaires to study participants and wider industry respondents to gauge attitudes towards UsHF and multimodal VR for engineering applications**

   As aforementioned, gaining the opinion and expertise directly from industry is extremely important at all research stages, but particularly during stages of infancy. Satisfaction of this objective will aid formulation of future UsHF research and applications. This will be achieved via the use of questionnaires administered to individuals who are both in industry and are based within the field of engineering.

See *Figure 1.4-1* for a summary of the aims and which objectives will facilitate their attainment.

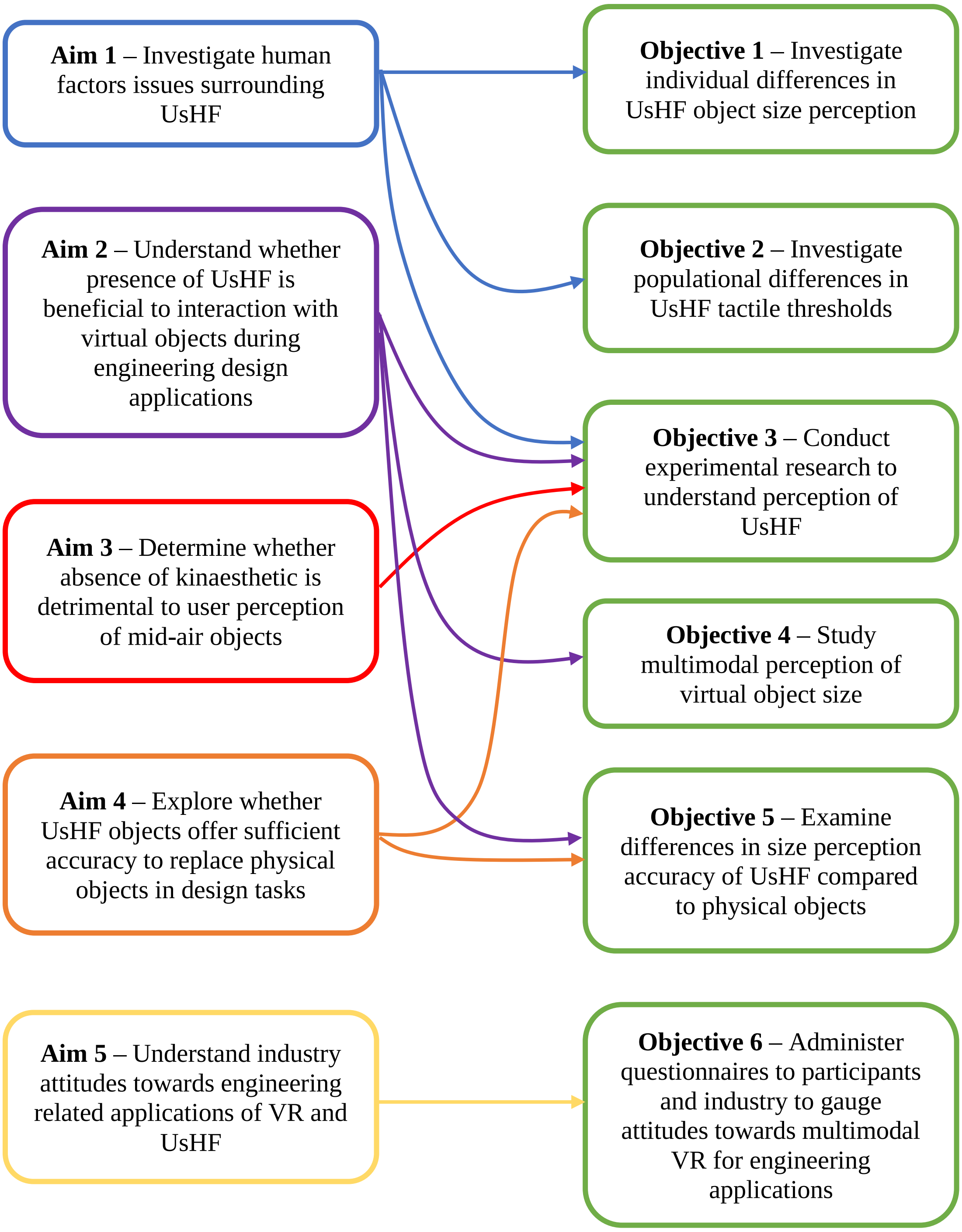


Figure 1.4-1. Diagram showing how the aims will be satisfied by the relevant objectives with colour coding to signify route origin.

1.5. Contribution

The research conducted for this PhD aims to contribute to several areas of deficit from the prior academic literature. As UsHF is a new technology, at present, there is only one publication that addresses human factors-related queries surrounding UsHF (e.g., Rutten, Frier, Van den Bogaert, & Geerts, 2019), and thus, only one taking a nuanced approach to understanding perception of UsHF stimuli. Furthermore, there is currently no literature that aims to support the integration of UsHF with a multimodal virtual engineering design application. As a result, it remains unclear how individuals perceive novel, UsHF stimuli and how it affects interaction with virtual objects and other attributes of UsHF, particularly objects and attributes relevant to engineering design.

With the increasing availability of UsHF solutions and tools that allow for its integration into existing systems, this research is being conducted during a window early in the development lifecycle of UsHF, and thus, should improve future applications of the technology, particularly within, but not limited to, the field of engineering design. The research to be conducted for this thesis also comes at a relevant time, with the COVID-19 pandemic encouraging a paradigm shift in the way we work, with remote working whilst limiting contact with shared surfaces becoming more relevant by the day. For successful implementations of UsHF, it is imperative that research addresses the perception and human factors considerations of UsHF in a detailed manner. In doing so will facilitate more accurate and useable VR-UsHF interfaces, thus improving designer’s workflow, the design process and the final product.

Chapter 2: Literature Review

2.1. Scope of Review

This chapter consists of a review of the literature relevant to the sense of touch, haptic feedback, VR and the individual elements surrounding the field of engineering design. As the subject of this PhD – Ultrasound Haptic Feedback (UsHF) - is a relatively new and novel technology, there is a broad focus on haptics in general due to a lack of UsHF-specific literature, whilst incorporating new publications that do investigate UsHF. The review begins by exploring the nature of the sense of touch and its relevance to interaction with everyday objects. Further attention is given to the importance of kinaesthesia/proprioception, individual differences, and sensory dominance/prioritisation during the process of object interaction, as these areas informed the experiments that follow this review. Later, interest is turned to multimodal interaction with virtual objects and indeed, Virtual Reality (VR). The reviewed material includes the relevance of haptics and VR in isolation, but also their application in engineering activities, such as design and prototyping. The chapter culminates in reviewing UsHF specifically in order to aid understanding of how the technology works, what it is capable of offering potential users as well as some of the foreseen limitations.

2.2. The Sense of Touch

On the surface, touch could be relegated in terms of importance to a position behind vision and hearing, but there is more to feeling than meets the eye. The sense of touch comprises of kinaesthetic/proprioceptive and tactile (cutaneous) sensations that are detected by various parts of the body. Kinaesthetic sensations are torques and forces that are detected by tendons, joints, and muscles, whereas tactile (cutaneous) sensations are vibrations, pressures, and shear forces, and are detected by mechanoreceptors located within the skin that respond to mechanical pressure and distortion (Culbertson, Schorr, & Okamura, 2018). Mechanoreceptors are particularly important for tasks that require fine motor control (Johansson & Flanagan, 2009). More on these two distinct haptic mediums is presented in sections 2.2.1 and 2.2.2 respectively. Combined, the various networks of receptors are known as the somatosensory system. In understanding the components that make up the somatosensory system and the roles they play, we can begin to understand what basic tasks might be like in their absence. For example, an individual receiving object hardness information allows them to judge the grasping strength in order to grasp it effectively, temperature information enables them to determine whether to grasp it at all, and proprioceptive feedback, which in basic terms allows the individual to move their limbs to a desired location and receive feedback on movements. Without the aforementioned examples of touch perception, an individual may not be able to apply adequate grasping strength, could interact with dangerous objects or even not be able to guide their limbs to the correct position in space to initiate object interaction.

Despite the importance of touch during everyday life, Robles-De-La-Torre (2006) inferred that the sense of touch is overlooked and not often considered as important as other senses, such as vision and hearing. This inference would appear valid, as subjectively, individuals are likely to favour other methods of perception that they bestow more trust in. The underestimated importance of touch could be due to a number of factors. From an individual perspective, it is easy to discount the subtle nature of haptic and touch feedback in favour of more immediate and detailed information gathered via the eyes and ears. Due to individual underestimation of touch sensations, there has been far fewer publications on the subject when compared to the visual system, particularly within fields such as VR. Further difficulties arise when considering sense of touch from a researcher's point of view. The sense of touch is likely to be overlooked because it is not easy to impair an individual's ability to receive haptic feedback, meaning the chance to study the importance of the sense of touch by inducing its absence is only possible using methods that require highly skilled individuals to administer anaesthetics to block transmission of tactile signals (Nowak, et al., 2001), artificially induced brain deafferentation techniques such as Transcranial Magnetic Stimulation (TMS) (e.g., Harris, Miniussi, Harris, & Diamond, 2002) or in cases of rare neurological conditions (e.g., Nowak, Glasauer, & Hermsdörfer, 2004). It is only upon investigating such rare conditions that disable an individual's ability to receive somatosensory information that we can begin to understand the difficulties of living without a sense that is underestimated in its usefulness.

In order to understand the importance of somatosensation, a case study exists of a patient called Ian Waterman (IW) who suffered severe nerve damage, permanently disabling his sense of touch, though leaving his motor control intact (Cole, 1995). Though he retained the ability to sense temperature and pain, the case of IW offers a rare insight into life without the sense of touch. During the study of IW, researchers highlight several normal tasks that were severely impaired or impossible without being able to feel touch, for example, chewing and speaking. Notably though were the difficulties he experienced simply controlling his body in what should have been a motionless state, something many people would take for granted. In a neutral position, IW's fingers and arms would often move around unintentionally. Trying to remain sitting upright or move by standing up or walking took IW two months and nearly two years respectively. He overcame these obstacles by learning to compensate for his lack of tactile intuition by using vision to understand his position in space. Thus, as we can see the impact an impaired or completely disabled somatosensory system can have on simple tasks, it is pertinent to explore the various elements of the human haptic experience.

2.2.1. Kinaesthesia and Proprioception

The terms 'kinaesthesia' and 'proprioception' are often used interchangeably, though some research suggests that they indeed have nuanced differences (e.g., Bastian, 1887; Sherrington, 1906), who both differentiated between how kinaesthesia should only encompass 'movement sense' and proprioception should refer to 'position sense'. Modern works suggest there to be little to no difference in the terminology due to the fact that limb movements are almost always associated with limb position (Stillman, 2002). Proprioception relies on mechanosensory neurons which are present throughout the human body (in this context), and are located within the tendons, muscles and joints, these are referred to as 'proprioceptors'. Proprioceptors can be summarised in three categories, muscle spindles found within the skeletal muscles, Golgi tendon organs which interface muscles and tendons, and joint receptors located in joint capsules (Tuthill, 2018). Though there are few examples, rare cases exist that study individuals who lack proprioceptive capabilities, which helps us understand the extent to which these seemingly autonomous processes have on everyday life. One of these examples (e.g., Cole, 1995) is explored in a previous (2.2) and later section (2.4.2), however, there is another example of an individual with brain and nerve damage that is pertinent to summarise for this section. Upon studying her case, it was discovered that she lacked the ability to eat effectively after losing proprioceptive feedback from the lower part of her face. She struggled to chew and swallow and was forced to develop manual techniques to achieve a superficially simple task. Rather surprisingly, she even struggled to keep her mouth closed as she was unaware of its position (Cole & Paillard, 1995).

Thus, the perception of haptic information from objects appears to be reliant on both cutaneous and proprioceptive feedback, the latter of which allows us to understand dynamic object information such as shape, size, curvature, hardness, and weight (Gallace & Spence, 2014; Giachritsis, Wright, & Wing, 2010). The absence of this information can result in severely impaired ability to reach, grasp, and maintain grasping strength

2.2.2. Object Manipulation

Whilst not something we consider often, the ability to manipulate objects with not only a high degree of accuracy, but also force, is an anatomical feature gifted by human evolution. It is posited that the human hand developed into its current state by evolutionary selection which favoured those who possessed hand dexterity and strength that facilitated effective ‘clubbing’ and ‘throwing’ (Young, 2003). Though the object manipulation process is simple on a superficial level, the actual processes that contribute to the action are very complex, and encompass seemingly autonomous consideration of texture, hardness, size, curvature, force, pressure, and torsion, as well as attributes of the hand, fingertip, skin, and joint kinematics (O’Shea & Redmond, 2021). These evolutionary developments allow us to yield proficiency in reaching and grasping from as young as four years old (Paré & Dugas, 1999). With maturity and experience, knowledge of object properties such as weight, size, and material as well as knowledge of the object use, are learned, thus giving an individual reference points on how a particular object can be interacted with (Lucaites, Venkatakrishnan, Venkatakrishnan, Bhargava, & Pagano, 2020). When object interaction plans are formulated based on prior knowledge, the brain also predicts the sensory feedback that should occur in conjunction with the interaction, which allows for the comparison between expected and experienced interaction, thus determining whether goals have been achieved. In doing so, an individual is seamlessly able to monitor progress and adjust motor commands for errors that contradict previous knowledge of sensory events (Flanagan, Bowman, & Johansson, 2006), this is particularly relevant for grip force control (Nowak, Glasauer, & Hermsdörfer, 2004). However, despite the importance of existing mental models, research demonstrates that cutaneous feedback is necessary to intermittently update object attributes in order to facilitate accurate interaction. This is shown during studies using deafferented (interruption of sensory nerve impulses) participants in which they were subject to an object manipulation task. It was discovered that the deafferented individual applied inefficient and inaccurately timed grasping force to objects (Nowak, Glasauer, & Hermsdörfer, 2004).

Not only are existing mental models of interaction important during object manipulation, but tactile signals are particularly crucial during this process, and are said to be imperative for skilful and dexterous object manipulation (Jenmalm & Johansson, 1997). This is thought to occur via a system of cutaneous mechanoreceptors which is believed to be the primary coding source for initial and sustained mechanical interaction events, which in turn provides information contributing to internal representations of object grasping and manipulation (White, 2012). Broadly speaking, there are four types of mechanoreceptor located in the skin: two reside only in the glabrous skin which covers the palm of the hand and fingers, and two reside in both the glabrous and hairy skin. See Table 2.2-1 for a summary of these mechanoreceptors, their location, and other properties.

Table 2.2-1. *Mechanoreceptor types and their attributes. All mechanoreceptors have a 5ms response time to detect stimuli and 20ms to detect stimuli order.*

Mechanoreceptor Types	Location	Sensed Parameters	Stimulation Type	Stimulation Frequency (Hz)	Spatial Resolution (mm)
Meissner Corpuscles	Glabrous Skin	Skin motion	Velocity, flutter, slip and grip control	2-40	3-5
Merkel Disks	Glabrous Skin	Skin motion and sustained skin deformation	Skin curvature, pressure, form, texture and edges	0.4-10	0.5
Pacinian Corpuscles	Glabrous & Hairy Skin	Skin motion	Vibration, acceleration and roughness	100-1000	20
Ruffini Endings	Glabrous & Hairy Skin	Skin motion and sustained skin deformation	Skin stretch, lateral/ static force and motion direction	0.4-100	10

The four mechanoreceptors noted in Table 2.2-1 can be considered to contribute to perception of cutaneous (tactile) sensations which is an essential, but not the only component of the object manipulation process (see section 2.2.1 for more information on kinaesthesia). Indeed, the lack of cutaneous sensation, elicited via the use of anaesthetics, has been demonstrated to significantly reduce grip force and increase the likelihood of dropping objects (Augurelle, Smith, Lejeune, & Thonnard, 2003).

Additional to the underlying processes of cutaneous and kinaesthetic feedback which contribute to successful object manipulation, vision also plays a significant role when manoeuvring physical objects. Object interaction can be dissected into two phases:

reaching and grasping. During the reaching phase, there is an emphasis on visual feedback which is initially used to determine the object location and inform the individual where to move their hand, this phase is also when the anticipatory grasp type is chosen (Cesanek & Domini, 2018). For example, the elected grip type to grasp a torus would be different compared to a sphere, which can be informed by a number of object attributes, such as size, type, and position (Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012). During the second phase, grasping is modulated not only by the aforementioned past experience, but also by the visual system, which again relies on determination of object characteristics to ensure the selected grip type is well executed (Stone & Gonzalez, 2015). However, due to the visual emphasis placed on manipulation of familiar objects, it is worth nothing that when presented with novel stimuli, tactile information increases in relevance, this is witnessed during tasks that utilise the ‘vertical-horizontal illusion’ (Fairhurst, Travers, Hayward, & Deroy, 2018). Furthermore, gaze is important for pre-empting movements, with gaze shifting to contact locations before the hands, such as the point of grasping, the target of where the object is being moved to, and the object when it arrives at the target location (Johansson, Westling, Backstrom, & Flanagan, 2001).

2.2.3. Size Perception of Physical Objects

Though not the only relevant attribute of an object, size is posited to play an essential role in the recognition and subsequent manipulation of it (Wing & Wimperis, 2008). Despite this, size perception does not receive nearly as much attention in the literature as for example, distance perception. This can be explained in part due to the fact that a significant proportion of publications suggest the process of object size perception is one that is achieved via object knowledge, familiarity and perception of the distance from the object, though this is debated. Some research suggests that size perception is not borne out of distance cues, but is a standalone process that does not rely on the other posited information processing mechanisms (Haber & Levin, 2001). Indeed, via experimental research, Haber and Levin (2001) determined object size perception to be a mechanism independent of the distance perception process.

In terms of size perception of close target objects, research indicates that size perception is a process of understanding hand spread distance in tandem with kinaesthetic information captured at the event of an object contacting the fingertips by rapidly adapting (RA) and slowly adapting (SA1) mechanoreceptors (Park, Han, & Lee, 2019). Specifically, kinaesthetic/proprioceptive cues provide feedback on hand posture (Burke, Gandevia, & Macefield, 1988) and cutaneous information informing the individual of object surface properties (Berryman, Yau, & Hsiao, 2006). Not only are tactile and proprioceptive properties relevant during the establishment of object size, but also prior object knowledge (as aforementioned in section 2.2.1 and 2.2.2) and object-hand scale mental models. The importance of object size perception should not be understated, as the way we perceive object size often guides behaviour and decision making with regards to planning and executing object interaction (Kristensen, Fracasso, Dumoulin, Almeida, & Harvey, 2021).

2.2.4. Size Perception of Virtual Objects

As in the physical world, accurate object size in virtual worlds is also paramount for some of the reasons mentioned in Section 2.2.3, but also for factors specific to VR, such as avatar embodiment and presence (Banakou, Groten, & Slater, 2013). The absence of accurate perception of size within VR can have undesirable implications for the VR experience, namely to body/avatar ownership and presence, both of which allude to the sense of ‘being there’ within the VE, as well as manipulation (Kim, Ryu, Son, & Han, 2022). It is posited that a significant proportion of a user’s ability to discern object size within VR comes from scaling of the virtual avatar, particularly the avatar’s hands (Ogawa, Narumi, & Hirose, 2017). In the aforementioned research, it was demonstrated that the avatar can have a significant impact on how users perceive the size and distance of virtual objects, with oversized avatars eliciting underestimation of object size, and undersized avatars having the opposite effect on size perception.

The application of haptic feedback has been investigated in order to improve perception of virtual objects, with an emphasis on more effective size perception and grasping, both of which are essential to the object manipulation process, physically, but particularly within VR (Park, Han, & Lee, 2019). Despite efforts to understand how haptic feedback can improve such interactions, the literature is not exhaustive, likely due to the relative infancy of haptic technologies and the complexity of the problem. Research by Park et al. (2019) highlights this complexity in a study of haptic feedback for virtual object size perception and demonstrates that though haptic feedback can have a significant impact on how virtual object dimensions are perceived, the type of haptic feedback can also affect perception. They note specifically that employing feedback which utilises skin stretch (as is common when manipulating physical objects), users report objects to feel larger than they are, and vibrotactile feedback to cause objects to feel smaller than without the feedback. This suggests haptic solutions should employ a combination of kinaesthetic and cutaneous feedback to the user to improve perception of virtual object size. Furthermore, the objects themselves can have an impact on accurate manipulation dependent on size Kim et al., 2022).

2.2.5. Individual Differences in Touch

There is well founded evidence to suggest the presence of individual differences in ability to detect tactile information (e.g., Abdouni, et al., 2017; Bruce, 1980; Gallace & Spence, 2014; Kalisch, Ragert, Schwenkreis, Dinse, & Tegenthoff, 2009). On a cognitive level, it is suggested that these differences could be due to changes in the somatosensory cortex as a result of learning, age, different uses and injuries (Kalisch, Ragert, Schwenkreis, Dinse, & Tegenthoff, 2009). Notably, the hands, which are able to discriminate touch information more effectively than the rest of the body, have the largest proportion of the somatosensory cortex dedicated to them relative to their physical size (Gallace, Tan, & Spence, 2007). Interestingly, these cortical differences are said to manifest in the form of increasing mental hand representations. This term alludes to how physical parts of the body, for example, finger length and overall hand size are represented in the brain. Mental representations of physical body parts, particularly the hands, is salient because of how it affects an individual’s interaction with the physical world, whereby effective interaction with the environment is achieved by understanding body shape, size and location (Cocchini, Galligan, Mora, & Kuhn, 2018). Kalisch et al. (2009) note that with the increase in age and changes in the somatosensory cortex, the mental representation of Euclidian distance (length of a line segment between two points) between participant’s index and little fingers also increased. Haggard and Jundi. (2009) even suggest that mental representations of the surrounding environment changes in line with the individual’s representation of their body, going as far to suggest this would affect the way objects within said environment are perceived. This means the objects within an environment could be perceived differently on an individual level depending on the neural representation of their hands and the space around them. These points are pertinent for UsHF because cortical hand representations could directly influence how different users will perceive the size and shape of objects projected in mid-air.

Object size, amongst other cutaneous information is gathered through the mechanoreceptors located in the skin, which require contact between the individual and the object. It is the receptors located in the glabrous skin found on the palm of the hands and foot soles that are of particular interest, as research has shown these areas to be subject to change and differences between individuals (e.g., Gallace & Spence, 2014; Thornbury & Mistretta, 1981). Thornbury and Mistretta (1981) studied dominant index fingers of fifty-five individuals. During the study, it was concluded that individual’s tactile threshold increased with age, meaning their sensitivity to touch sensations decreased as the sample aged. The researchers stipulate that this finding could be due to skin properties which are affected by age, such as thinning of the epidermis, lower levels of elastin and less collagen present (Thornbury & Mistretta, 1981). This investigation sought to build upon previous works that had limited samples, and in doing so giving further argument for the existence of individual differences in tactile sensitivity.

During a study mentioned prior, Kalisch, et al. (2009) not only highlight the presence of increasing cognitive hand representations with age, but they also discover a significant reduction in tactile discrimination abilities in both dominant and non-dominant index fingers, which in turn correlated with increasing age. They further insinuate that these changes are not only correlated with changing cortical hand representations, but that they are also due to decreasing densities of the mechanoreceptors located in the glabrous skin, and slower conduction velocities in the peripheral nerves. Interestingly though, during the same investigation, it was suggested that the effects of aging on cognitive hand representations and tactile sensitivity are not inevitable. Instead Kalisch et al. (2009) suggest performance can be restored by means of training and learning, stating the role the decline in mechanoreceptors plays as being potentially minimal. It is then possible to speculate that individuals in a similar trade or field may be subject to different rates of decline in tactile sensitivity when compared to the general population, due to training and use of learned knowledge. This notion of practice effects being prevalent in tactile discrimination is also evident in other studies. For example, Hodzic, Veit, Karim, Erb and Godde (2004) used fMRI to determine that repeated stimulation of body parts can lead to improved tactile discrimination, evidenced by increasing activation across the somatosensory cortex.

The aforementioned points become particularly important when considering UsHF applications within 3D design, where the objects created within the design suite are intended to be to scale. Emphasis on points of individual differences then become especially important when users are hoping to replace physical prototyping stages with accurate VR prototypes. When considering the effects learning can have on the accurate interpretation of tactile information, it is possible to deduce that those who become well versed in using UsHF within a design context, or indeed other applications, will be more effective than those who are in the early stages of adoption. It could be imperative that a comprehensive training program be implemented depending on the application in order to elevate new users to the same level of proficiency with the technology. If training is not provided, it is possible to forecast differences in the efficiency and accuracy of workers, due to their limited experience using tactile feedback to aid the process it has been applied to (Hodzic et al., 2004).

Typically, in many investigations of individual differences a common area of interest lies in variations between the two genders, this is also of interest in differences of tactile sensitivity. Within the current literature, the interest in gender differences in the context of touch appears to have foundation. For example, research has shown females to be able to detect finer differences in grooved and smooth surfaces compared to their male counterparts (e.g., Goldreich & Kanics, 2006). The ability for females to detect finer tactile details is thought to be resultant of several biological factors. Research suggests that the Meissner corpuscles and Merkel discs located in the dermis of the fingers are denser in female fingers than a male (Peters, Hackeman, & Goldreich, 2009). Not only is the density of the receptors mentioned prior of interest, but the density of the fingerprint ridges is also believed to be partially responsible for this difference in tactile acuity, as they present more densely on female fingers than male (Dillon, Haynes, & Henneberg, 2001). With this knowledge in mind, the literature proceeds to deduce that hand size must play a role, as generally speaking, female hands and fingers are smaller than male, whilst containing a denser population of receptors and physical ridges in and on the fingers (Peters et al., 2009). Though this inference is not an exact science as of course, some individuals of opposing genders may share the same finger size. In this instance a male and female with the same size fingers will share the same level of tactile sensitivity according to Peters et al. (2009), as the number of receptors does not change, only the density based on size of the hand and fingers.

2.3. Sensory Dominance and Prioritisation

Sensory dominance and prioritisation are well investigated topics within the literature. In this review, there will be a focus on sensory dominance over tactile senses as that is one of the interests of this PhD, though there exists a wide body of research on the prevalence of visuo-audio, visuo-olfactory/taste and audio-haptic dominance. An excellent illustration of sensory dominance is the well-established ‘rubber hand illusion’, in which subjects are presented with a false hand in place of their own, it is then touched or stroked by an experimenter in synchronicity with their own hand which is hidden. Eventually, when viewing the artificial hand being interacted with, subjects report feeling as if the rubber hand is their own, thus taking ownership of the artificial hand (e.g., Botvinick & Cohen, 1998; Rohde, Di Luca, & Ernst, 2011). The rubber hand illusion demonstrates interesting and valuable insight into how vision can dominate the haptic senses. This phenomenon extends to other studies of visuo-haptic dominance. During a study in which participants were asked to run their hand up and down a straight meter-rule whilst wearing glasses that distorted their vision, participants perceived the ruler as being curved. The authors further discovered that when subjects closed their eyes, they would perceive the ruler as being straight (Gibson, 1933).

Tactile dominance is witnessed in studies of the perception of surface texture. For example, research has found that tactile information can be prioritised over visual cues during a divided attention task. For example, one study suggests that reaction times to tactile stimuli are unaffected when attention is divided between tactile, auditory and visual senses, but reaction time to visual and auditory stimuli increased, thus suggesting that in some instances, tactile information is prioritised above other sensorial feedback (Hanson, Whitaker, & Heron, 2009). Another interesting example of tactile dominance over visual is seen when individuals are presented with a physical object in the shape of a letter, which they view mirrored, but feel in the correct orientation. This study found that despite subjects experiencing two different versions of a letter, for example, feeling ‘b’ but seeing ‘d’, participants more regularly suggested that the letter they were presented with was the one they were feeling, not seeing, i.e., ‘b’ (Heller, 1992).

Indeed, the design process, particularly in architecture, is often visually driven, with little regard for the tactile qualities of designs before they are constructed. Research demonstrates that architecture students are primarily driven by visual elements when designing, even when asked to consider tactile elements of objects, such as warmth (Wastiels, Schifferstein, Wouters, & Heylighen, 2013). The authors go as far as to suggest that students did not know what common building materials felt like to touch, and thus could not identify them when only exposed to their tactile properties. This, the authors insinuated, has a negative impact on the finished product, as it does not account for user interaction with the final designs (Wastiels, Schifferstein, Wouters, & Heylighen, 2013).

Researchers posit that the rationale for this visual bias can be due to several factors. Firstly, it is likely that individuals favour visual feedback because it is the modality that usually affords the most accurate interpretation of an environment (Spence, 2016). Others suggest that the reason vision dominates the sensory experience is a matter of sensory latency. Specifically, when considering the time it takes to convert sensory information into neural signals that can be processed, it takes ~40µs for auditory input, ~2ms for tactile input, and ~50ms for visual input (Hanson et al., 2009). That being said, this is dependent on the distance from the stimulus, as the effect of processing latency diminishes with increasing distance of the stimulus to the recipient, at which point vision and audition become more reliable. Based on the aforementioned latency to process the sensory information of interest, it can be noted that sound is processed at a significantly faster rate than both tactile and visual stimuli, with visual processing being significantly slower than both other modalities.

Based on the literature, it is possible to infer that the basis for either visual or tactile dominance is situational, and not a broad-spectrum assumption for all instances, this is known as the ‘modality appropriateness hypothesis’ (Hecht & Reiner, 2009). This hypothesis stipulates that vision may dominate touch for macro-geometric properties, that is, structural attributes and relatively rough surface texture, whereas touch may dominate vision for micro-geometric scenarios, in which objects have very fine surface differences.

2.4. Virtual Reality for Engineering Applications

Within this section, Virtual Reality (VR) is introduced and explored. In the context of engineering. VR used to produce virtual environments (VEs) can be defined as a technology which metaphorically removes the user from reality and injects them into an entirely artificial world in which the user has the ability to enact agency upon (Zheng, Chan, & Gibson, 1998). VR can, in theory, embody most senses (vision, touch, sound and smell), but often only provides users with visual and auditory feedback (Bailey & Bailenson, 2017). VR is said to provide the user of a virtual environment with the sense of “being there” (Bowman & McMahan, 2007). Some stipulate that VR should encompass three properties; presence, interactivity and immersion (Walsh & Pawlowski, 2002). Presence is said to refer to the feeling of ‘being somewhere’ and links to Bowman and McMahan’s (2007) notion of VR; interaction is self-explanatory, but the level of interaction facilitated by the VE is posited to affect the level of perceived presence. The meaning of immersion, however, is regularly disputed in the literature. On one hand is the narrative which states that immersion is measurable based on subjective experience of VR based on spatial, sensory-motoric (movement feedback), emotional and cognitive immersion (when users feel they can solve complex problems) (Bjork & Holopainen, 2005). Other authors propose that immersion is measurable quantitatively based on elements such as inclusiveness (how well reality is excluded), extensiveness (the number of sensory modalities), surroundings (amount of the VE viewable), vividness (the visual fidelity, such as resolution and richness) and matching (how well received feedback matches body movements) (Slater & Wilbur, 1997).

Computer Aided Design (CAD) has been dominant within engineering design for decades, so it is natural for the process to evolve to employ newer and more effective technologies that address the existing issues within the CAD process, some of which are considered in section 1.3, but in summary include; inclusive design, reduced cost, time savings and early detection of issues before constructing physical prototypes. Indeed, there are many examples of implementations to alleviate some of these issues in the literature. Examples of VR design review date back as early as 1998, at which point an implementation was created to review designs of mechanical products, though the VE was rudimentary due to hardware limitations associated with the time period (Kremer, 1998). An investigation into a system called 'VRSmart' (see *Figure 2.4-1*) yielded slight improvements to the detection of 3D design faults when compared to a CAD software design review approach. The study also cites advantageous effects of the system on communication between design teams (Wolfartsberger, 2019).

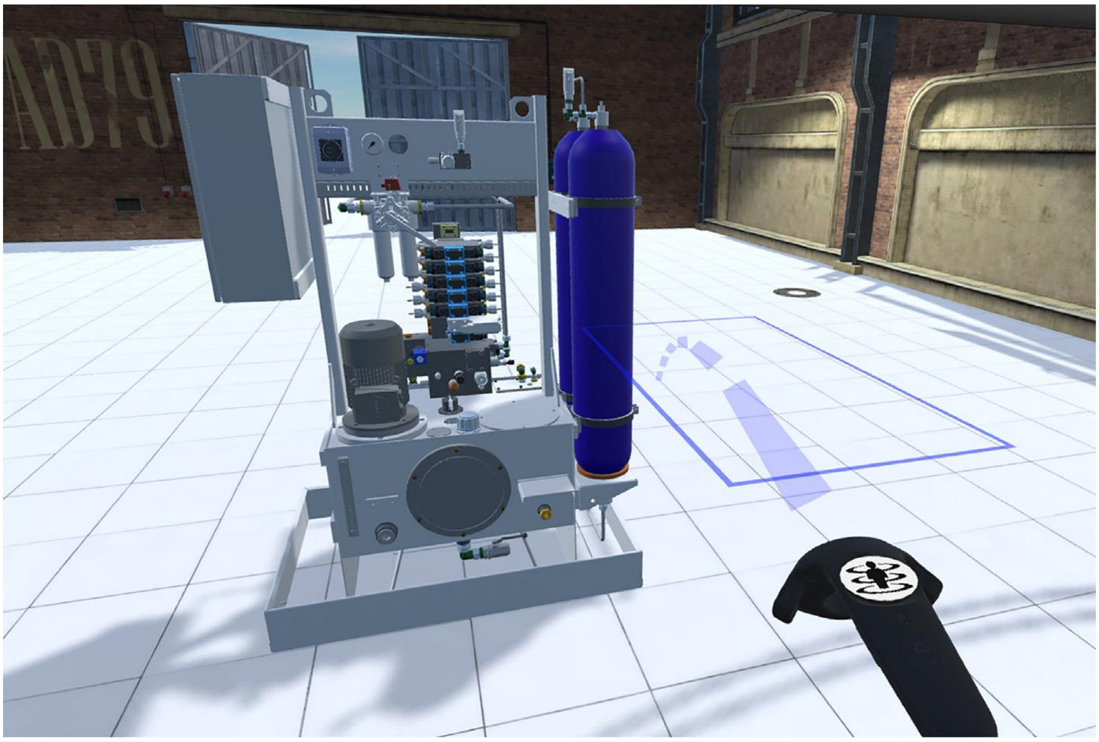


Figure 2.4-1. An example user view of a 3D VR CAD power unit prototype (Wolfartsberger, 2019).

VR construction design reviews have also been implemented, in which the authors report significant time and cost savings (Bassanino, et al., 2010). Indeed, reports suggest that VR implemented to support the design review process in the automotive industry have improved the quality of review outcomes, whilst simultaneously reducing cost and time to market (Lawson, Salanitri, & Waterfield, 2015). Researchers have also implemented relatively complex multimodal VR systems for industrial design review, in which users were provided with both visual and haptic feedback when interacting with complex designs that can be assembled and disassembled.

Users during this study reported that the system was easy to use and learn, which has positive implications for time and cost saving, they also reported that the system facilitated communication between designers, engineers, and assembly operators (Wolfartsberger, Zenisek, Sievi, & Silmbroth, 2017).

The prototyping stage is another facet of the product design process that VR could improve, as it offers demonstrable improvements when using interactive prototypes in place of corresponding physical prototypes (Ferrise, Bordegoni, & Cugini, Interactive virtual prototypes for testing the interaction with new products, 2013) and can facilitate correction of design errors before construction (Berg & Vance, 2017). Other literature suggests that VR prototyping can improve design elements to offer better ergonomics, layouts, tooling design, serviceability and maintenance (Seth, Vance, & Oliver, Virtual Reality for Assembly Methods in Prototyping: A Review, 2011).

Collaboration between designers, CAD engineers and stakeholders is a benefit often cited in the literature and is supported by studies which investigate these impacts (Bordegoni & Caruso, Mixed reality distributed platform for collaborative design, 2012). For example, a system known as ‘AutoEval MKII’ promises to bridge the gap between CAD engineers and those without CAD training or a technical background by employing a 3D virtual interface controlled with a motion-detecting glove for intuitive interaction with 3D virtual objects (Naef & Payne, 2007). There is also literature to support the use of VR collaborative design of garments for sufferers of Scoliosis in which the designer interacts directly with the user, affording versatility not offered by traditional 2D design (Hong, et al., 2017). Product lifecycle management (PLM), an innately collaborative process has also been embedded into a VR environment for effective visualisation and communication of designs across various teams (Mahdjoub, Monticolo, Gomes, & Sagot, 2010).

Bruno and Muzzupappa (2010) conducted three experiments in order to establish the viability of VR for participatory design, that is in summary, when the end user is involved during all stages of the design process in order to optimise the end product. Their findings from these studies suggest firstly that VR was found to be a viable alternative to traditional product interface usability testing, citing their success in evaluating the usability of a microwave and electric oven. Secondly, it was possible for the participants to effectively evaluate product prototypes, during which they were able to collect product improvement suggestions from the users. Finally, the authors cite success in involving end-users in the product design process for the sake of improving the final product. Despite the successful testing of participatory design, Bruno and Muzzupappa (2010) do suggest there to be potential limitations in participatory design due to the controlled nature of the studies, postulating that it is not necessarily representative of ordinary product use. They also suggest that the lack of haptic feedback could be detrimental, particularly when considering limitations in dexterity/force requirements for testing interface controls.

Depending on the field, traditional training methods can often be dangerous, time consuming, expensive and require physical space that may not be available when necessary, or at all (Adams, Klowden, & Hannaford, 2001). Training through VR offers increased flexibility and safety that may not be available through traditional means. For example, there is a strong case for the use of VR in undergraduate and postgraduate engineer training. In a study which employed a 3D immersive virtual environment for engineering education, the authors state observable benefits by reducing costs, reducing exposure to hazardous materials and the opportunity to explore inaccessible locations, such as chemical reactors, just to name a few (Abulrub, Attridge, & Williams, 2011). Another interesting engineering-related example of VR being used when traditional methods were costly or implausible to recreate, was during NASA’s Hubble Space Telescope repair mission simulation, during which it was concluded that the training method improved flight crew performance (Loftin & Kenney, 1995).

2.4.1. Multimodal Virtual Reality

Multimodality in the context of VR can be defined as a VR system that facilitates feedback via multiple sensory mediums, for example, vision, audio, touch and smell. Though it is possible to use VR with minimal sensory feedback, for example, just visual, or visual and audio (which is still technically classed as multimodal) which is most often the feedback combination used, the lack of other sensory information can hinder the user’s sense of immersion, with Burdea, Richard, and Coiffet (1996) insisting that real time multimodality is key to the authenticity of the user experience. Further to improving the user’s sense of immersion, multimodality is said to improve interaction with virtual objects (Nizam, et al., 2018). This is indeed corroborated by the literature which will be explored in section 2.5.1-4. At present there have been a number of effective implementations of multimodal VR which primarily consist of visual, auditory, and haptic feedback, though there are examples of systems which employ visual, auditory, smell and heat information to users for the purposes of VR fire evacuation training (Nilsson, et al., 2019), though these applications are not as common. As the context for this PhD is based on multimodality with visual and haptic feedback, it is not salient to explore other forms of multimodality in detail, for example, VR with olfactory or auditory feedback.

2.5. Haptics

The term "haptics" is derived from the Greek word "Haptikos" which means 'pertaining to the sense of touch'. In this context, haptics can be considered as manipulation through sensing tactile (cutaneous) and kinaesthetic/proprioceptive sensations (Sreelakshmi & Subash, 2017), which both work in cooperation to facilitate human perception of their environment, in turn allowing the individual to act on their environment (Hayward, Astley, Cruz-Hernandez, Grant, & Robles-De-La-Torre, 2004). Indeed, haptics involves active and serial exploration of a stimulus (Gallace & Spence, 2014). In engineering terms, haptics can be considered to encompass forces, shear forces, frequencies, elongations, and mechanical tensions, all of which are essential for the technical design process (Kern, 2009). Despite the term *haptics* encompassing both cutaneous and kinaesthetic feedback, there are examples of haptic feedback which produce only cutaneous and only kinaesthetic feedback, which will be explored later in this section. This section will summarise the existing haptic technologies, haptics in VR and the importance of haptic feedback.

2.5.1. Existing Haptic Technologies

There are a number of haptic feedback types, which broadly speaking fall into three categories, graspable, wearable, and touchable which will be explored below.

2.5.1.1. Graspable Haptics

Graspable haptic devices are usually fixed in position which allows them to provide the user with force feedback (kinaesthetic) which means users can experience intricate surface properties of virtual objects, such as; hardness, weight, texture, and resistance

(Culbertson, Schorr, & Okamura, 2018). Examples of graspable haptic interfaces include Phantom haptics, which are available in a several specifications, the best of which is a desktop device offering six-dimensional input with a usable area of 30x20x25cm and accuracy of 0.02mm (Kusumoto, et al., 2006). Another example of such a device is the Freedom 6S which has the ability to incorporate another axis, providing seven DoF and a maximum torque of 460mNm (Powers, 2007). See *Figure 2.5-1* for an example of these devices.

Figure 2.5-1. Phantom Premium 3.0 graspable kinaesthetic haptic device (Phantom 3D systems, www.3dsystems.com/haptics-devices/3d-systems-phantom-premium).

Due to the nature of these types of haptic devices, for example being able to provide over six DoF, resistance and force feedback, they are often used for; surgical simulation, teleoperation, and CAD. When considering some of the benefits and drawbacks of graspable haptics such as those aforementioned, they are naturally application specific, for example, it would not be viable to implement a Phantom haptic device for gaming, so those drawbacks will not be considered. Instead, they will be considered on a technological rather than application specific basis. Issues associated with graspable haptics such as the Phantom (*Figure 2.5-1*) include high cost, limited use cases and lack of mobility. Conversely, the benefits of these types of haptic devices are that they offer unparalleled fidelity and allow the user to experience interaction analogous to the real-world, as they often facilitate six or even seven DoF.

These benefits are particularly salient when considering the high stakes applications of such devices.

For example, a Phantom haptic device is used in conjunction with VR surgical simulation (NeuroTouch) to train would be surgeons in their craft before transitioning to real-world patients (AlZhrani, et al., 2015).

2.5.1.2. Wearable Haptics

On the opposite end of the spectrum to graspable haptics, wearable haptics usually offer only cutaneous (tactile) feedback and are usually mounted to parts of the body, often limited to the hands (Culbertson, Schorr, & Okamura, 2018). Wearable haptics are more commonplace, and thus there are more examples of such technologies in the literature and indeed, the general marketplace. Wearable haptics often induce tactile sensations via the use of vibrational forces directed to isolated parts of the body. Other wearable haptic devices can emulate virtual objects by providing the user with skin pressure and stretch feedback to mimic collisions, object hardness and surface texture. For example, Spagnoletti, et al. (2018) developed a fingertip-mounted device that provides the user pressure and vibrational feedback, achieved via a system of pulleys that manoeuvre a platform on the fingertip to increase and decrease pressure and a voice coil actuator which allows the device to convey virtual textures. Vibrotactile tactors are often used for wearable haptic devices due to their simplicity and relative ease of implementation, for example, wireless vibrotactile gloves have been used for telemanipulative grasping (Galambos, 2021). Haptic gloves/hand exoskeletons are the more complex counterpart to the device mentioned previously and can offer more realistic force feedback. Technologies such as the HaptX DK2 haptic glove utilises a pneumatic system that can deliver 36N of force to each finger for kinaesthetic feedback, and microfluidic skin with 2mm skin displacement for cutaneous feedback to the fingertips (HaptX, 2022). Though there are many examples of haptic gloves in the literature, they tend to be practically unviable due to cost, weight, complexity, and lack of mobility. Finally, full body haptic suits exist primarily to provide low fidelity haptics for gaming such as the bHaptics Tactsuit which can exert cutaneous feedback to the user's torso via the use of vibrotactile motors (bHaptics, 2022). See *Figure 2.5-2* for examples of wearable haptics.

Figure 2.5-2. Fingertip haptic device (left) (Spagnoletti, et al. (2018) and HaptX DK2 haptic glove/hand exoskeleton (right) (HaptX, 2022).

2.5.1.3. Touchable Haptics

Touchable haptic devices are the least common of the three device categories but are nonetheless relevant. Touchable haptics can be considered under the umbrella term of ‘haptic surfaces’ or 'haptic displays' which generally use pin arrays to mimic the physical properties of virtual objects as the hand explores them. For example, pin arrays under rubber membranes have been used to create small-scale shapes in teleoperation and VR (Wellman, Peine, Favalora, & Howe, 1998), ActivePad is a tactile pattern display which facilitates modulation of coefficient of friction (Mullenbach, Johnson, Colgate, & Peshkin, 2012) and Project FEELEX is a haptic surface consisting of an actuator array below a flexible surface which has visual imagery projected down onto it (Iwata, Yano, Nakaizumi, & Kawamura, 2001) (see *Figure 2.5-3*).

Figure 2.5-3. Project FEELEX haptic surface device. (Iwata, Yano, Nakaizumi, & Kawamura, 2001).

While these technologies are interesting as proof of concepts, they lack industry support and have relatively few practical applications compared to other types of haptic devices due to their cumbersome, complex, and often low fidelity nature.

2.5.1.4. Mid-Air Haptics

Though Culbertson, Schorr and Okamura (2018) only mention the three aforementioned haptic device categories, recent developments in haptic technologies create a new category, ‘mid-air haptics’. With the growing interest in mid-air visual displays, for example displays that use reflection and refraction to manipulate a light source, such as ‘PortOn’ (Koizumi & Sano, 2020), which affords tether free interaction with virtual images, the natural progression would be to explore methods to provide users with untethered haptic feedback to compliment such a display. Such technologies exist and strive to produce high quality mid-air stimuli that can be touched and felt without the need for complex and cumbersome haptic devices. These technologies show promise in a number of applications, such as mid-air visual displays, VR and gesture displays.

There are two notable technologies that fall into the mid-air haptics category. Initial ambitions to create a mid-air haptic experience were done so by using air jets absorbed by a ‘receiver’ held in the user’s hand, paired with visual stimulus (Suzuki & Kobayashi, 2005) (see *Figure 2.5-4*).

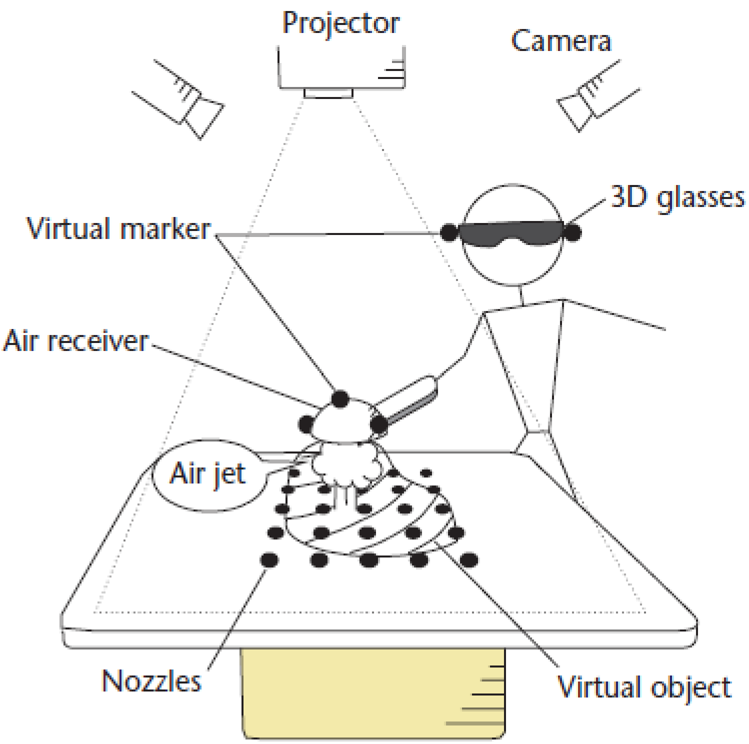


Figure 2.5-4. A diagram of air jet driven force feedback (Suzuki & Kobayashi, 2005).

Though an interesting concept, the limiting factor in this implementation is the ‘receiver’ that must be used to capture the air jets. The requirement to use such an object hinders natural interaction with virtual objects, as there is no way for a user to use their hands to experience the stimuli as they would with a physical object. There are also limited applications for this system, which appears to be constrained to the realms of interactive entertainment as opposed to practical applications. Furthermore, the solution is unable to produce multidirectional force, further limiting positional applications.

An evolution of air-jet haptics was developed, but instead uses air vortex rings (Gupta, Morris, Patel, & Tan, 2013). Though the principle behind utilising air vortices is not a new one, the potential to apply them for haptic feedback is relatively recent. The authors state that the premise for the device is to provide realistic haptic interaction at a distance, with the justification being that most users of virtual environments are often meters away from the computer/console. Though the findings of Gupta et al. (2013) were promising, the reality is again, that this technique for providing haptic feedback lacks fidelity, and has a number of other drawbacks, such as high latency between firing and receipt of the vortex, a theoretically limited number of vortices that can be produced in quick succession, as well as excess noise from the mechanism that creates the vortices.

Ultrasound haptic feedback is the final and most convincing case for the mid-air haptic category, but will be assigned its own section below due to it being the focus of this thesis.

2.5.1.5. Ultrasound Haptic Feedback

A major issue associated with existing haptic feedback devices is the requirement to be in physical contact with them, the level of which varies depending on the specific device. For example, the user of a ‘haptic glove’ must wear the device as if it were a normal glove, and although it could render virtual surface textures physically, it could also limit the user’s hand movements (Sreelakshmi & Subash, 2017). At the other end of the spectrum is the full body exoskeleton, which has all of the issues associated with the haptic glove, but on a much larger scale. Principally, it is likely that movements whilst using an exoskeleton would feel unnatural due to the presence of mechanical friction, something that does not exist whilst performing normal, unencumbered movements. In such a scenario, it is possible that the user be overly conscious of the presence of the haptic device, feeling *it* rather than the simulated interactions with the virtual world (Gallace & Spence, 2014). The drawbacks associated with physical haptic devices have led researchers to investigate alternative means to provide users with haptic feedback in a non-invasive manner.

Using ultrasound to create haptic sensations is a relatively new concept. Early efforts to create UsHF can be traced back to the 1990’s, though this attempt relied on the use of water to transmit ultrasonic waves, which subsequently had to be received by an acoustic reflector attached to the fingers of the user (Dalecki, Child, Raeman, & Carstensen, 1995). Much like the air jet method of Kobyashi (2005) which also relied on the use of a ‘receiver’, the work of Dalecki et al. (1995) was impractical considering the benefits UsHF has later shown to have. The earliest work using ultrasound transducers to generate mid-air focal points was initiated by Hoshi, Takahashi, Iwamoto and Shinoda (2010) (see *Figure 2.5-5*). This study functioned effectively as a proof of concept for the incorporation of UsHF with a tactile display and hand tracking, demonstrating that the technology could be used to create artificial mid-air haptic sensations.

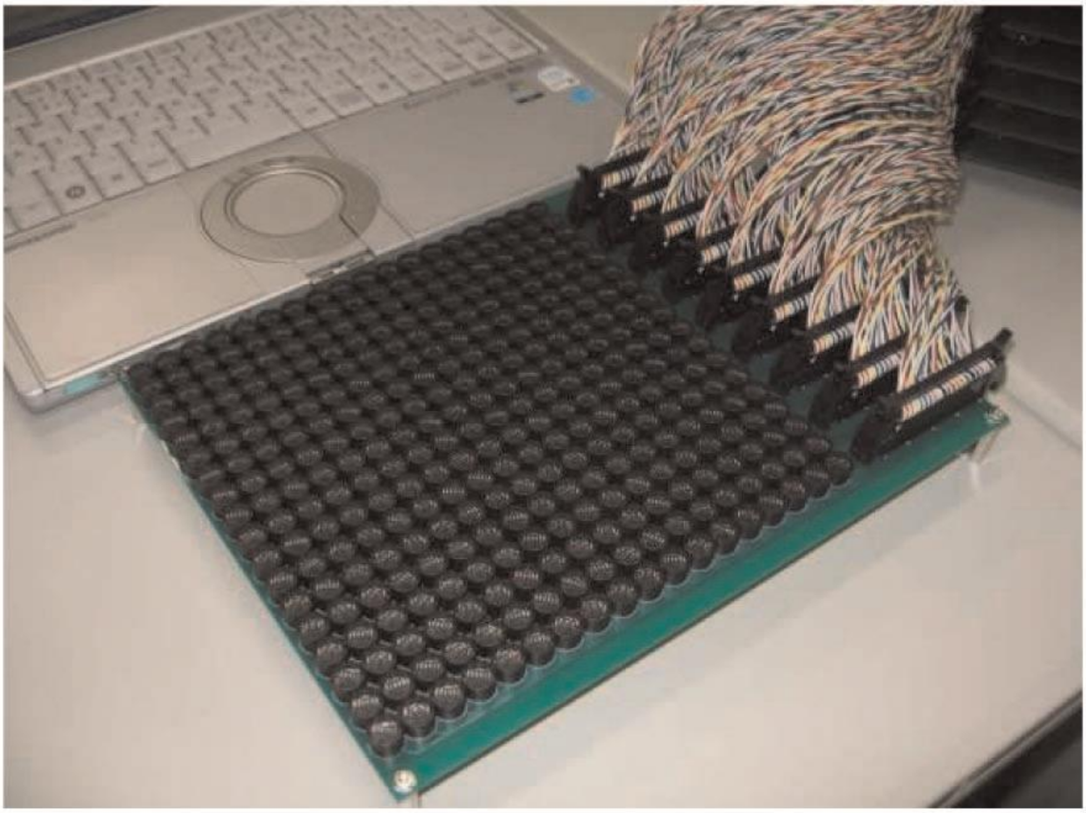


Figure 2.5-5. Early ultrasound haptic feedback array consisting of 324 ultrasonic transducers (Hoshi et al., 2010).

Later, Ultraleap (previously Ultrahaptics) commercialised the technology and brought a viable ultrasound haptics device to market. Ultraleap demonstrated that the technology could be manufactured in a small, mobile, and versatile package which offers the ability to plug-and-play as well as integrate the technology with both new and existing software. Early research explored how the technology could accurately render virtual shapes in mid-air, whilst positing applications for UsHF in VR, touchless interfaces, and interactive museum exhibits (Long, Seah, Carter, & Subramanian, 2014).

Although Ultrasound Haptic Feedback (UsHF) can only currently be applied to the hand effectively, removing physical interaction with a haptic device means the user is relieved of the physical constraints associated with invasive haptic devices that impact range of movement, or movement effort. This means the user is able to use their hand without it being contorted by the likes of a haptic glove.

Both the device used by Hoshi et al. (2010) and more recent technology such as the array offered by Ultraleap (e.g., Carter, Seah, Long, Drinkwater, & Subramanian, 2013) utilise the same principles to create mid-air haptic feedback. Sensations are created in mid-air by focussing ultrasound called Acoustic Radiation Force (ARF). The ARF creates a shear wave within the skin tissue which in turn stimulates the mechanoreceptors in the skin responsible for transmitting touch sensations.

UsHF has been applied in several contexts with some success. For example, within entertainment, UsHF has been used to add haptic feedback to a VR rhythm game (Georgiou, et al., 2018) and to compliment a children’s wizard game in which players could cast spells within VR (Martinez, Griffiths, Biscione, Georgiou, & Carter, 2018). Interaction with virtual displays is another area in which UsHF has made progress, with effective implementations of the technology for interaction with virtual-visual buttons (Rümelin, Gabler, & Bellenbaum, 2017), 2D acoustically transparent displays (Carter, Seah, Long, Drinkwater, & Subramanian, 2013) and gesture displays in cars (Shakeri, Williamson, & Brewster, 2018), the latter of which reducing the amount of time driver’s eyes were off the road.

Despite the freedoms UsHF affords, the technology is in the early stages of the development process and is not a complete solution. UsHF fails to provide the user with many tactile sensations that may be pertinent to its success and usability. Specifically, UsHF cannot simulate object hardness, surface texture or temperature (e.g., Carter et al., 2013). That being said, it is likely dependent on the application of the technology as to whether those deficits translate into real world issues. For example, surface texture and object hardness and temperature are not likely to be required for a touchless display, but may be necessary for more intricate applications, such as engineering assembly simulation.

2.5.2. Haptics in Virtual Reality

In understanding Ian Waterman's condition (Section 2.2), we can begin to understand the importance of tactile information and the impact the lack of it can have on both simple and complex tasks. What can be deduced from the study of Ian Waterman is the similarity of his disorder to an able-bodied individual acting in a virtual environment, where vision is the primary and often only cue for spatial positioning. This assumption is enforced by users of telesurgery, during which surgeons can operate on patients remotely with robotic arms and a telemanipulator (Choi, Oskouian, & Tubbs, 2018). During surgical procedures, for example, it is often necessary to receive an amount of tactile feedback to understand the behaviour of the patient's tissue. Because this is not usually possible, some doctors report that their vision is required to compensate for substitute missing tactile feedback, something which requires further cognitive resources and vast amounts of practice to perfect (Gallace & Spence, 2014). Despite being able to make these inferences, it is important to understand the true effects lack of haptic feedback can have on individuals acting within a virtual environment. In order to understand the effects lack of haptic information can have within virtual environments, it is first important to understand the principle behind increased sensory information in such a context.

The quest to immerse users in virtual environments and make them seem more realistic is achieved through the concept of 'presence'. High levels of presence are often associated with the individual feeling as if they are present in the virtual world (Riva, Waterworth, & Waterworth, 2004; Sanchez-Vives & Slater, 2005). Not only has presence been shown to increase the perceived realism of virtual environments, but increased presence has also been demonstrated to illicit emotions in users, with research highlighting an interaction between presence and both positive and negative emotional responses, in this instance, anxiety and relaxation (Riva, et al., 2007).

The main difference between the case of Ian Waterman and VR users is that individuals acting within a virtual environment still have an element of proprioceptive feedback from their physical bodies. When considering motionless states, where Ian Waterman could not keep his limbs stationary, users in a virtual world receive this information from their physical body, preventing their virtual avatar from moving. The larger issue comes when those in a virtual world attempt to interact with virtual objects.

During these interactions, it becomes essential that the user be provided with touch information about the virtual object they are attempting to manipulate. Like Ian Waterman, deficits in this information could become particularly problematic in contexts that require fine motor control, such as surgical simulations (e.g., Botden, Torab, Buznik, & Jakimowicz, 2008; Panait, et al., 2009) or when interacting with a 3D design of a prototype (e.g., Seth, Su, & Vance, 2006), as haptic feedback is even more critical to successful task performance in these types of tasks.

As there is a continuing endeavour to produce more immersive and realistic experiences, it is more pertinent than ever to understand the significance of haptic feedback in more specific contexts, such as user interfaces, training, design, prototyping and for general virtual object manipulation.

2.5.3. The Importance of Haptic Feedback

The importance of haptic feedback in virtual environments should not be overlooked, as it can afford the user a number of benefits compared to non-tactile virtual environments, some of which will be outlined in this section. Despite the importance of object size perception in the manipulation process, the research conducted into general object size perception is limited, this is also the case for size perception of virtual objects using synthetic haptic feedback.

Research into different forms of haptic feedback reveal some interesting findings on how the presence or absence of cutaneous and kinaesthetic feedback affects size perception. For example, Park, Han and Lee (2019) highlight that the presence of cutaneous information does not affect perception of object size, but with the omission of such feedback, grip force on virtual objects increased significantly. Furthermore, they found that giving the users skin-stretch feedback resulted in them perceiving objects as larger than they did without, whereas vibrotactile feedback elicited a miniaturising effect, whereby participants perceived object sizes to be smaller than without vibrotactile feedback. These results demonstrate that not only can haptic feedback impact the perception of virtual object sizes, but that it also depends on the type of feedback provided, suggesting that the haptic medium employed should be tailored to the specific application and desired outcomes.

Other research by Son & Park (2018) demonstrated that kinaesthetic haptic feedback directed at the thumb, middle finger and index finger and cutaneous feedback to the palm can effectively improve perception of large virtual objects compared to kinaesthetic feedback only (Son & Park, 2018). Relatedly, an investigation conducted by Wuillemin, Van Doorn, Richardson and Symmons (2005) found that virtual spheres with visuo-haptic feedback were deemed significantly larger than when given the same task with virtual visual-only information.

Considering depth perception, haptic feedback is a viable mechanism to address the well-established inaccuracy in virtual environments for which mean perceived egocentric distances (distance from observer to object) are approximately 74% of the modelled distance, otherwise known as 'depth compression' (Renner, 2014). This margin of error in underestimation of distances in virtual environments is posited to be as a result of several factors, such as; hardware errors, software errors, and differences in human perception, even in complex virtual environments (Kenyon, Phenany, Sandin, & Defanti, 2007). Haptic technologies could offer a solution to prevent or minimise VR distance underestimation, which can also impact reaching and object perception. Though there is limited literature on the subject, research has also demonstrated how a combination of vibrational and force feedback can be used in VR to significantly improve depth perception by 8.3 times when compared to no haptic feedback, and also demonstrates significant improvements with only vibration feedback, or force feedback delivered separately when compared to no haptic feedback (Makin, Barnaby, & Roudaut, 2019).

2.6. Haptics for Virtual Engineering Applications

As was discussed during the multimodal VR section (2.3.1) this section will explore in detail, the application of haptic technologies within virtual engineering applications. Exploration of this element will be split into several sections; haptics in virtual design, prototyping, manufacturing, and training, giving an insight into how haptic interfaces can be applied, their benefits, and drawbacks.

2.6.1. Haptics for Virtual Design

Due to the inherently tactile nature of the design process, haptic feedback for virtual design is one of the most relevant applications of haptics within the realms of VR engineering design. Some authors go as far as to suggest that the adoption of 2D computer interfaces, such as mice, or styli designers have stifled their natural desire to explore and manipulate their creations tactically (Mahoney, 2000). As a result, Larsson and Torlind (2001) suggest that the implementation of haptic technologies to the CAD process could significantly improve the product development process whilst also reducing cost.

During an experiment in which the authors implemented a haptic device to convey tactile information of aesthetically driven virtual concepts for industrial design, it was reported that the system was well received by professional designers, stating that they felt they were in close connection with the models and that it allowed them to convert their perception of the object surface into a mathematical representation (Bordegoni & Cugini, 2008). Though the authors do state that hardware limitations prevented detection of finer surface details, such as small holes and sharp edges in the virtual model. One investigation sought to implement force feedback via a Phantom device (see section 2.4.1.1) for CAD design, specifically force feedback was applied to the thumb and index finger to simulate object grasping (Burdea G, 1999). The author found that designers could more efficiently complete assembly of their designs in an immersive virtual environment with haptic feedback, compared to without. Other research into the use of haptic feedback for designing 3D CAD models suggests their implementation of ‘Virtual Design Works’ based on component technology (COM+) to offer increased flexibility in the design of complex surfaces (Liu, Dodds, McCartney, & Hinds, 2004). During several implementations of haptic feedback with 3D CAD models, Bourdot, et al. (2010) report promising improvements to gesture accuracy and execution times, with a particular emphasis on inclusion of direct contact feedback to users, as it was deemed to be received well by the users. Though the authors also highlight that at the time of writing, the technology was limited by poor free-hand gesture interactions.

2.6.2. Haptics for Virtual Prototyping and Assembly

In this context, virtual prototyping can be considered the use of virtual technologies to evaluate prototypes without creating a physical prototype, this includes both 2D virtual and 3D VR. It is worth mentioning that some literature explores design and prototyping terms simultaneously, and that a number of the inferences from virtual haptic design and prototyping investigations can be applied interchangeably. The first study of interest served as a proof of concept for the application of haptic feedback to testing prototypes of washing machine interfaces. Though the investigation did not collect data on the application's effectiveness, the authors demonstrated that the use case was possible and that it can be used to determine preferable knob behaviour (Ha, Kim, Park, Jun, & Rho, 2009). SHARP (System for Haptic Assembly and Virtual Prototyping) offers a look into the possibilities of VR and haptic feedback for prototyping and assembly. The system comprises of a dual hand haptic system featuring dual three DoF Phantom haptic interfaces paired with a VR HMD. The authors posit that users of the system are able to assemble complex CAD models which can also be used for training, thus improving product development time. However, they do state that the system lacks torque feedback, which they suggest is essential for perception of object collisions (Seth, Su, & Vance, 2006). An interesting application of consideration is the use of haptics during prototyping of everyday products to improve the final user experience. Ferrise, Furtado, Graziosi, and Bordegoni (2013) engage in a study of the usability of a dishwasher in which they digitise the existing product (though it is also possible to digitise pre-production elements). They were then able to artificially simulate the forces required to open the dishwasher door and tailor it to user preferences.

Testing the serviceability is another key area of interest within the realms of prototyping, studies investigating this process using virtual simulations of aerospace-related CAD models demonstrate that haptic feedback with six DoF can be implemented for such tasks. The researchers during this study found that the presence of force and torque feedback was helpful, going so far as to suggest that it would not have been possible in its absence (Cohen & Chen, 1999).

2.6.3. Haptics for Virtual Manufacturing and Assembly

Due to the number of humans involved in the manufacturing process, haptic feedback for VR manufacturing is paramount, particularly when attempting to make the virtual environment as close to the real thing as possible. An example of such an implementation is known as 'VMASS', the Virtual Manufacturing Assembly Simulation System, which as the name suggests, is a tool for training users in manufacturing and assembly using a semi-immersive virtual environment. This tool allows users to analyse designs and assembly process without having the physical components in front of them, and offers haptic feedback for collision detection (Al-Ahmari, Abidi, Ahmad, & Darmoul, 2016). The authors state this system is used to give real time performance feedback to trainees, allowing them to improve during manufacturing assembly tasks.

2.7. Haptics for Virtual Training

One of the fields that VR has been applied to most, is medical surgical training. With the growing complexity of surgical operations, and difficulty obtaining cadavers for training (Fortes, et al., 2016), it is no surprise that the medical industry has implemented both tele-surgical machines and VR for a safe and replicable training experience. The positive influence VR can have on training is becoming more apparent, particularly for minimally invasive surgery which requires high levels of dexterity and precision, and during which most if not all of the limitations of traditional training apply (Adams, et al., 2001). The benefits of VR training in medicine are evident, offering amongst other benefits, repetition of procedures, quicker adoption of new procedures and instruments, the ability to increase and decrease task difficulty based on user ability (scalability) and cost-effective training (Patel & Patel, 2012). Evidence to support the claimed benefits of VR training is demonstrated by several studies including that of Seymour et al. (2002), who found surgeons who trained using a VR simulator, were not only five times less likely to make an error during a Gallbladder dissection, but also completed the task 29% faster than residents who were not trained using VR. Further evidence for lower error rates after using VR training has also been demonstrated by other researchers (e.g., Ahlberg, et al., 2007; Scott, et al., 2000).

The benefits of VR training within medicine and particularly surgical applications are evident. However, given the high-stakes nature of surgery, it is imperative that the skills learned in the virtual world can be transferred to a real patient. During procedures, surgeons need to understand how certain tissues and other areas of the body respond to manipulation, particularly when creating incisions, suturing or grasping (Botden, Torab, Buznik, & Jakimowicz, 2008). Using the example given earlier of minimally invasive surgery, this requirement becomes more relevant as visual feedback is limited and the surgeon relies on haptic feedback received through their instruments (Botden, et al., 2008).

Possibly the most important factor when implementing a VR simulator for training purposes, is to ensure it facilitates the positive transfer of simulated skills and avoids the transfer of negative skills or bad habits to real world scenarios. Haptic feedback within surgical simulation is essential if trainees are to effectively transfer skills to real world applications, which is particularly important given the implications a mistake during surgery can have on the patient. Research has shown that VR training with haptic feedback leads to significantly improved skill acquisition by the trainee compared to the same training without haptic feedback (Aggarwal, Moorthy, & Darzi, 2004), as well as improved skills transfer to a real world surgical setting (Strom, et al., 2006).

2.8. Haptics for Other Applications

Though the focus of this PhD is in UsHF for multimodal engineering applications, UsHF has the potential to provide haptic feedback within fields that were previously inaccessible due to the aforementioned drawbacks to other existing haptic devices mentioned in this chapter.

Haptics have an important role to play within user interfaces, from the automotive industry to the accommodation of I.T users with visual impairments. In-vehicle touch screens with no haptic feedback, as is usually the case, can be susceptible to high error rates and slow interaction, and can often result in distraction from driving (Burnett, 2001). Haptic systems can be beneficial in this instance by alleviating some of the aforementioned drawbacks with traditional in-vehicle touch screens, which is seen in the literature. For example, ‘HapTouch’, a touch screen with haptic feedback has been demonstrated to significantly reduce error rates and interaction times during a simulated driving task. These findings are particularly salient as new cars are more commonly equipped with centralised touch screens instead of traditional buttons and dials. UsHF has been demonstrated to be beneficial when interacting with in-vehicle touchless displays that rely on gesture-based interaction. For example, Large, Harrington, Burnett and Georgiou (2019) demonstrate how an implementation of a gesture interface using UsHF to provide haptic feedback can reduce visual demand and errors whilst improving interaction speed during a simulated driving task.

In terms of accessibility, there is potential for haptic feedback to improve the lives of visually impaired individuals in their use of technology, which is salient when ensuring those who are currently unable to interact with computers are able to integrate successfully into a world of increasing reliance on IT. Solutions to aid visually impaired and blind users in a world dominated by vision, demonstrate that users can be provided with haptic feedback to convey web page information delivered via a Phantom haptic interface (Sjostrom, 2001). This concept was more recently explored and found that the use of haptic mice improved computer use in users who were blindfolded, which would in theory be replicable in visually impaired and blind users (Jaijongrak, Kumazawa, & Thiemjarus, 2011).

2.9. Chapter Summary

This chapter explored the literature focussing on various facets of the human sense of touch, sensory dominance, VR and haptic feedback in order to aid understanding of the context of the work carried out during this PhD. Initially this review highlighted the facets of the sense of touch that are essential for effective perception and manipulation of objects, the populational differences in those abilities and how some senses, for example vision, can often dominate others, like touch. Understanding these elements of touch are imperative when creating synthetic haptic stimuli for virtual interaction, as it means interfaces can be designed to combat or capitalise on the nuances of tactile exploration.

VR was demonstrated to be a valuable tool in various applications, particularly the engineering design process in which it has been shown to improve design time, efficiency, and costs, but not without its caveats, such as the lack of haptic feedback which can negatively affect user accuracy and immersion in the virtual environment. Furthermore, the literature highlights how haptic technologies can improve interaction with 3D virtual environments, particularly with regards to emulating grasping and collisions with virtual objects. Finally, the review explores a new technology, UsHF, which promises to offer a cheap, versatile, and easy to use haptic interface which can create tactile versions of virtual objects in mid-air.

However, this review has highlighted the lack of literature relevant to the human factors issues surrounding UsHF and perception of mid-air objects. It is imperative that future work addresses this deficit, as failure to understand the psychophysical perception of this relatively new and experimental technology could lead to issues later in the development lifecycle of the device, thus negatively affecting real-world applications. Furthermore, there is a general lack of understanding of the psychophysical perception of various types of haptic feedback, but particularly UsHF, this deficit is especially apparent with regards to object size and depth perception. It is also unclear how effectively synthetic haptic feedback can accurately replicate physical objects within virtual worlds, due to the aforementioned sensory biases.

The research conducted during this PhD should focus on populational differences in perception, as these are demonstrated in the literature to affect the sense of touch, perception of mid-air objects, for example, how size and intensity differences are interpreted by users, as well as understanding how well UsHF can be incorporated into multimodal environments that require accuracy and how well the aforesaid environments can replicate real world interaction.

Chapter 3: General Methodology

This chapter will outline the general methodology employed during this PhD. It will explain that a programme of research, incorporating experimental work using UsHF technology, and surveys of designers from industry, was conducted in order to determine the usefulness of this technology in engineering applications.

3.1. Research Framework

Ultraleap contributed to this research with funding in kind, by providing their device (UHEV1) and software. Due to the immaturity of the research field around UsHF technology, the research direction was initially driven by the existing literature based on the sense of touch, VR, general haptics, and other relevant topics mentioned during Chapter 2. This initial research determined the nature of the subsequent research, which kept the industrial partner's (Ultraleap) area of interest in mind, which was for the application of their technology within VR engineering applications. As such the research was based on Grounded Theory (Chun Tie, Birks, & Francis, 2019), for which the conclusions were derived from the data gathered from a primarily experimental programme of work. This approach meant that the research was tailored to areas relevant to industry-lead interests, yet also addressed gaps in knowledge. This was beneficial for the PhD as it led to a nuanced investigation of certain human factors of UsHF interaction that would have been unlikely had the research not been conducted from the ground up.

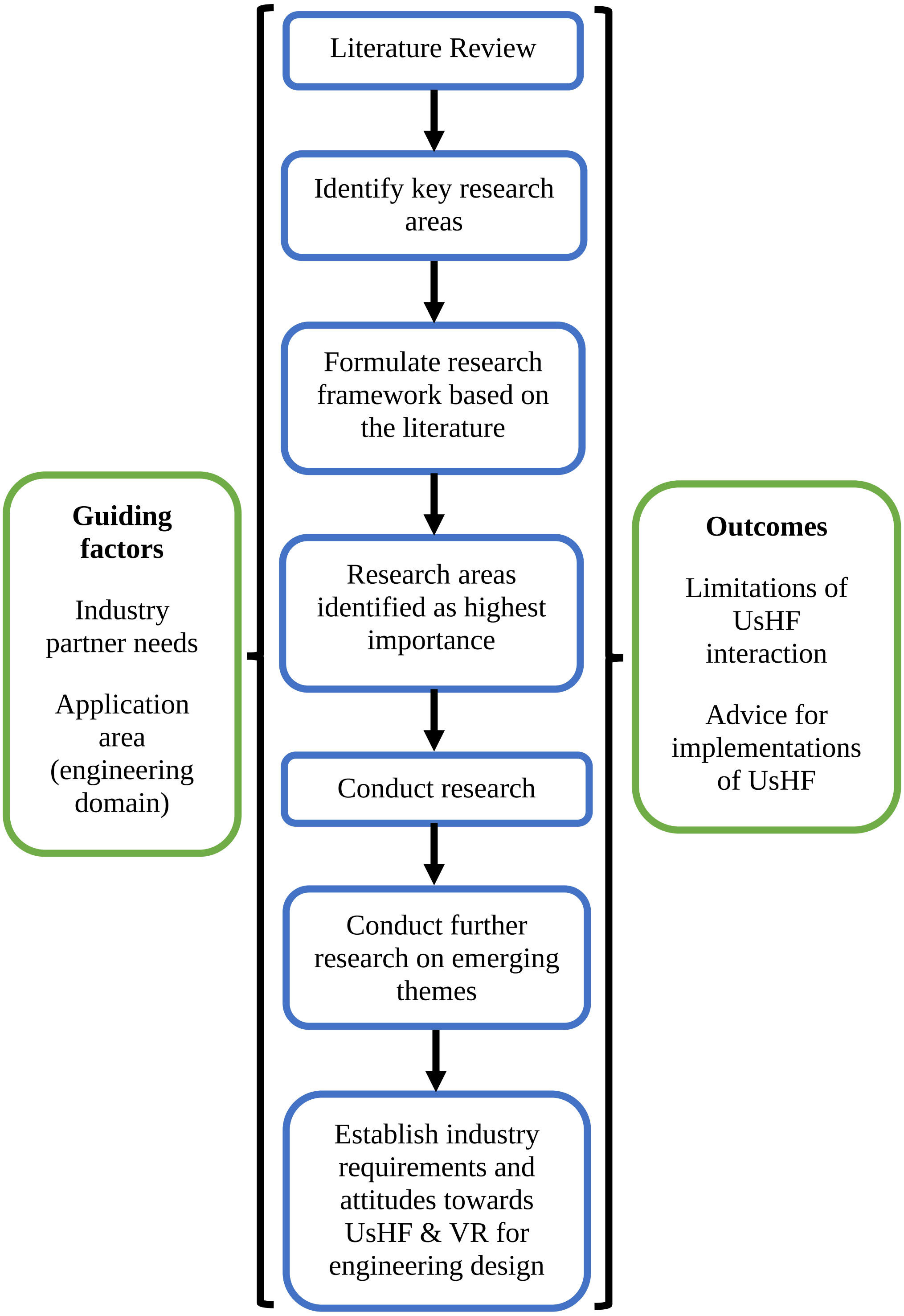
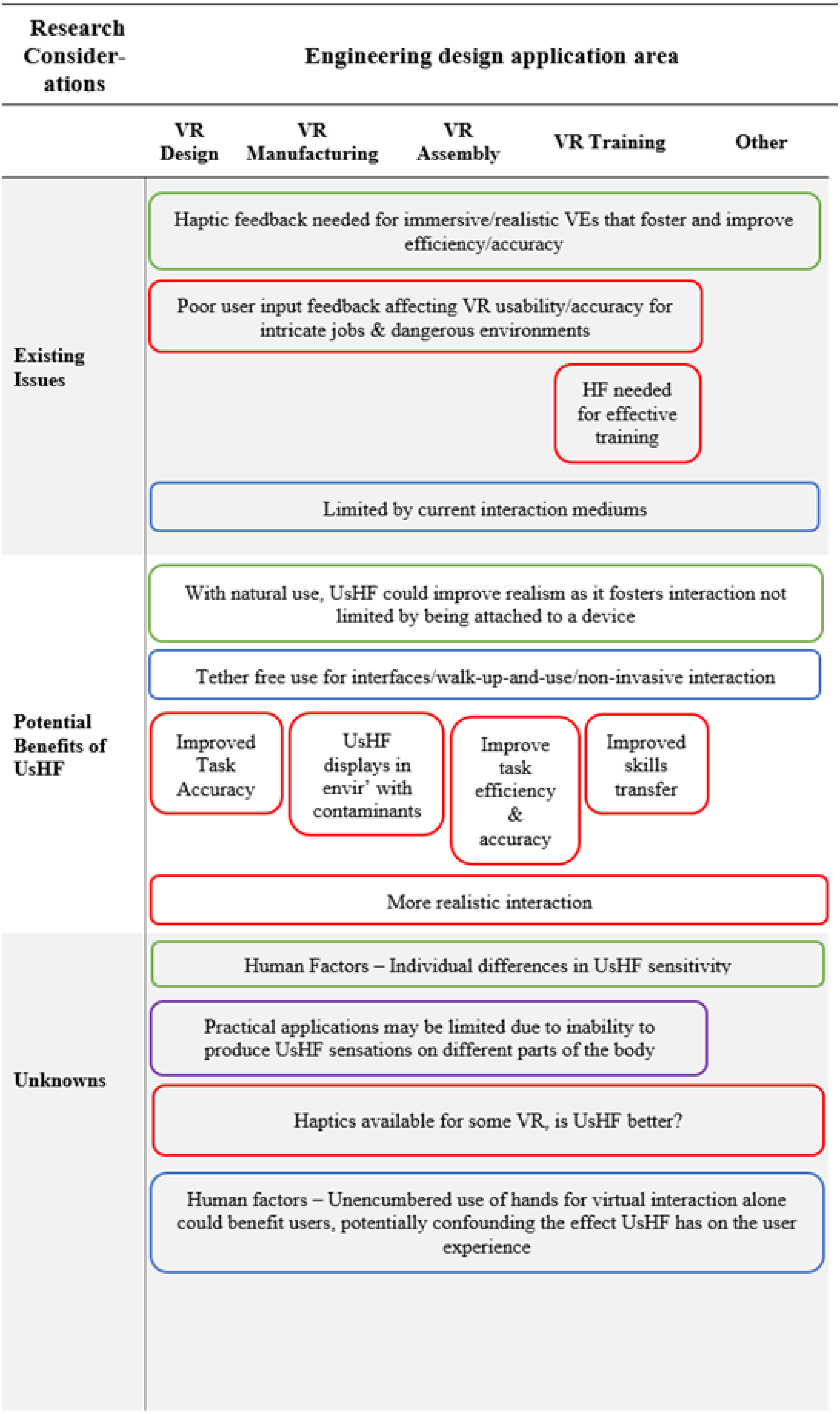


Figure 3-1. Timeline of research direction progression to identify key research areas.

Figure 3-1 illustrates that the research throughout this thesis was driven by not only the existing literature and gaps that current publications did not address, but that the research direction developed based on the emergent findings from each study, in line with the Grounded Theory approach (Chun Tie, Birks, & Francis, 2019).

As key areas of importance were established, they were plotted on a chart designed to further prioritise research avenues. This research framework is illustrated in *Figure 3-2*. It sought to first establish the existing issues within the various facets of engineering design, as well as external issues not necessarily within the field of engineering.



Research Consider-ations

Engineering design application area

VR Design | **VR Manufacturing** | **VR Assembly** | **VR Training** | **Other**

Existing Issues

Haptic feedback needed for immersive/realistic VEs that foster and improve efficiency/accuracy

Poor user input feedback affecting VR usability/accuracy for intricate jobs & dangerous environments

HF needed for effective training

Limited by current interaction mediums

Potential Benefits of UsHF

With natural use, UsHF could improve realism as it fosters interaction not limited by being attached to a device

Tether free use for interfaces/walk-up-and-use/non-invasive interaction

Improved Task Accuracy

UsHF displays in envir' with contaminants

Improve task efficiency & accuracy

Improved skills transfer

More realistic interaction

Unknowns

Human Factors – Individual differences in UsHF sensitivity

Practical applications may be limited due to inability to produce UsHF sensations on different parts of the body

Haptics available for some VR, is UsHF better?

Human factors – Unencumbered use of hands for virtual interaction alone could benefit users, potentially confounding the effect UsHF has on the user experience

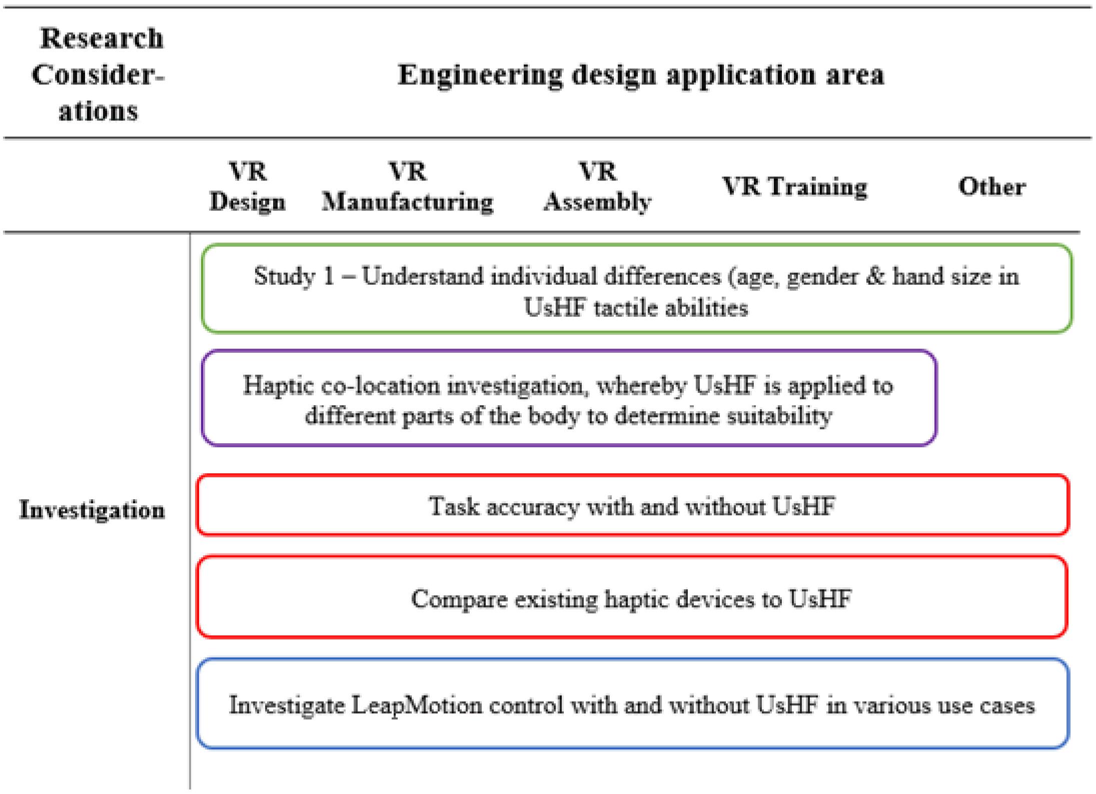


Figure 3-2. Research framework exploring existing issues, where UsHF could possibly solve them and how they could be investigated. Colour coding is used to track how each existing issue follows through to ‘potential benefits’, ‘unknowns’ and ‘investigation’. Box placement corresponds to each potential application, i.e., ‘virtual design and VR manufacturing’.

The issues highlighted do not represent *all* of the problems within the field, but were specific to VR engineering applications that were within the initial scope of the PhD. These issues were identified based on a review of prior literature (Chapter 2). The existing issues were colour coded in green, red and blue, which were then used to track the issues in subsequent sections. For example, the ‘green’ existing issue corresponds to the green potential benefits, unknowns, and so on. During this process, it was established that human factors issues, specifically individual differences in perception of UsHF was an important avenue of enquiry, as failure to understand the potential impact of any populational differences, could confound data collected during further studies.

Using the literature review and the research framework above, it was possible to further project an early path of the PhD through an investigation of individual differences in perception of UsHF (see *Figure 3-3)*.

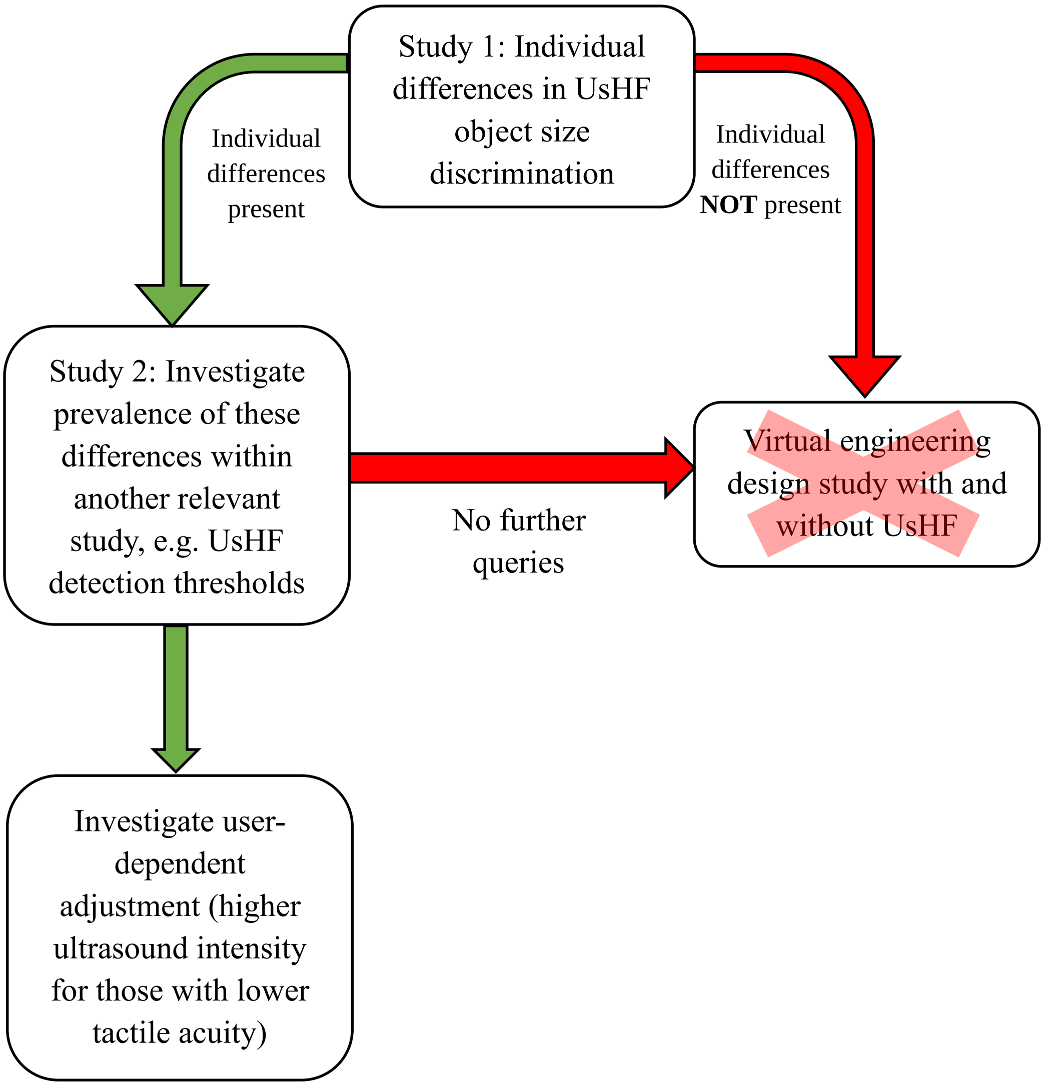


Figure 3-3. Decision tree exploring the research path in the presence/absence of individual differences whilst using UsHF.

Looking at *Figure 3-3*, it can be seen that based on the literature (Chapter 2), individual differences were identified as the most urgent and relevant research direction. A projection for the subsequent research direction was formulated whilst considering the possible outcomes of the initial research, i.e., whether individual differences were present when using UsHF or not. Initially, it was expected that if individual differences were not present, that the research could progress to *applied* studies, wherein UsHF could be implemented within an industry-specific study. However, while Study 1 did not find any evidence for individual differences, it did reveal some interesting results that warranted further investigation, particularly the role of intensity in perception of UsHF stimuli (Chapter 4). Thus, the original decision tree was adjusted to reflect this change of direction. This includes the redaction of progression to applied studies, as it was pertinent to explore the growing list of human factors related queries. From this initial decision tree, another was formulated to encompass new findings, see *Figure 3-4*.

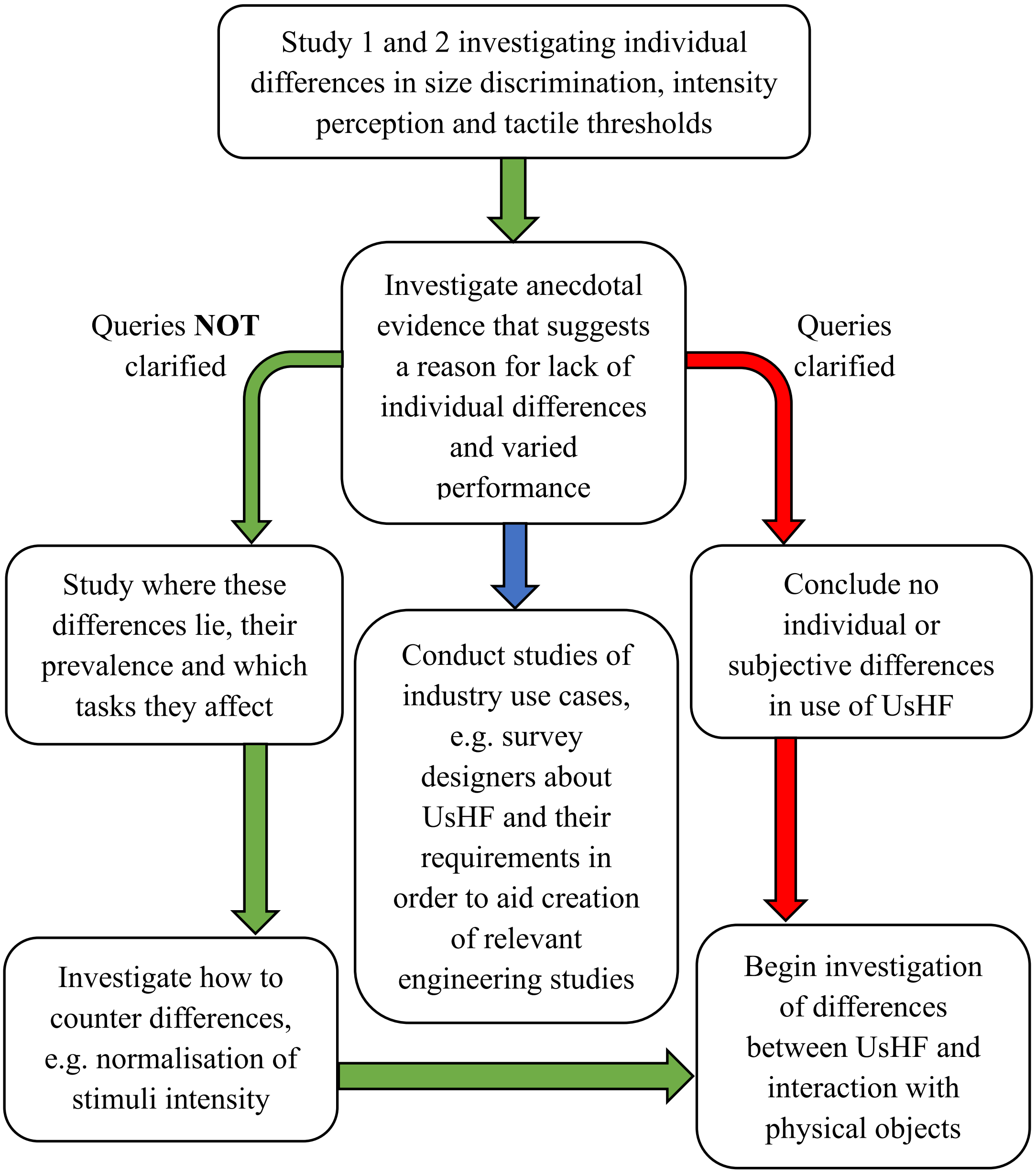


Figure 3-4. Revised decision tree which takes findings from Study 1 into consideration. The path taken was the green, ‘queries not clarified’ path.

As *Figure 3-4* illustrates, the initial stage proposed the investigation of anecdotal evidence gathered during Study 1 and subsequently Study 2, more information on which can be found in their respective chapters (4 and 5). As the initial stage raised more questions about perception of UsHF objects, this PhD followed the ‘queries not clarified’ (left) path. The central (blue) path could be and indeed was pursued regardless of the outcome of the first stage, as it was deemed salient to explore industry opinion to aid construction of future studies, but also to indicate which areas of engineering should be focussed on for future applications of UsHF. Furthermore, after the first and second studies, it was deemed that applied investigations of UsHF would not be possible, both due to the impact of the COVID-19 pandemic and the prior research work needed to understand UsHF perception. Thus, it was proposed that psychophysical trials would conclude with an investigation into how well UsHF can replicate physical objects, as this is the intended application of UsHF within engineering design. Thus, the final structure of the research studies, organised by chapter, can be seen in *Figure 3-5*.

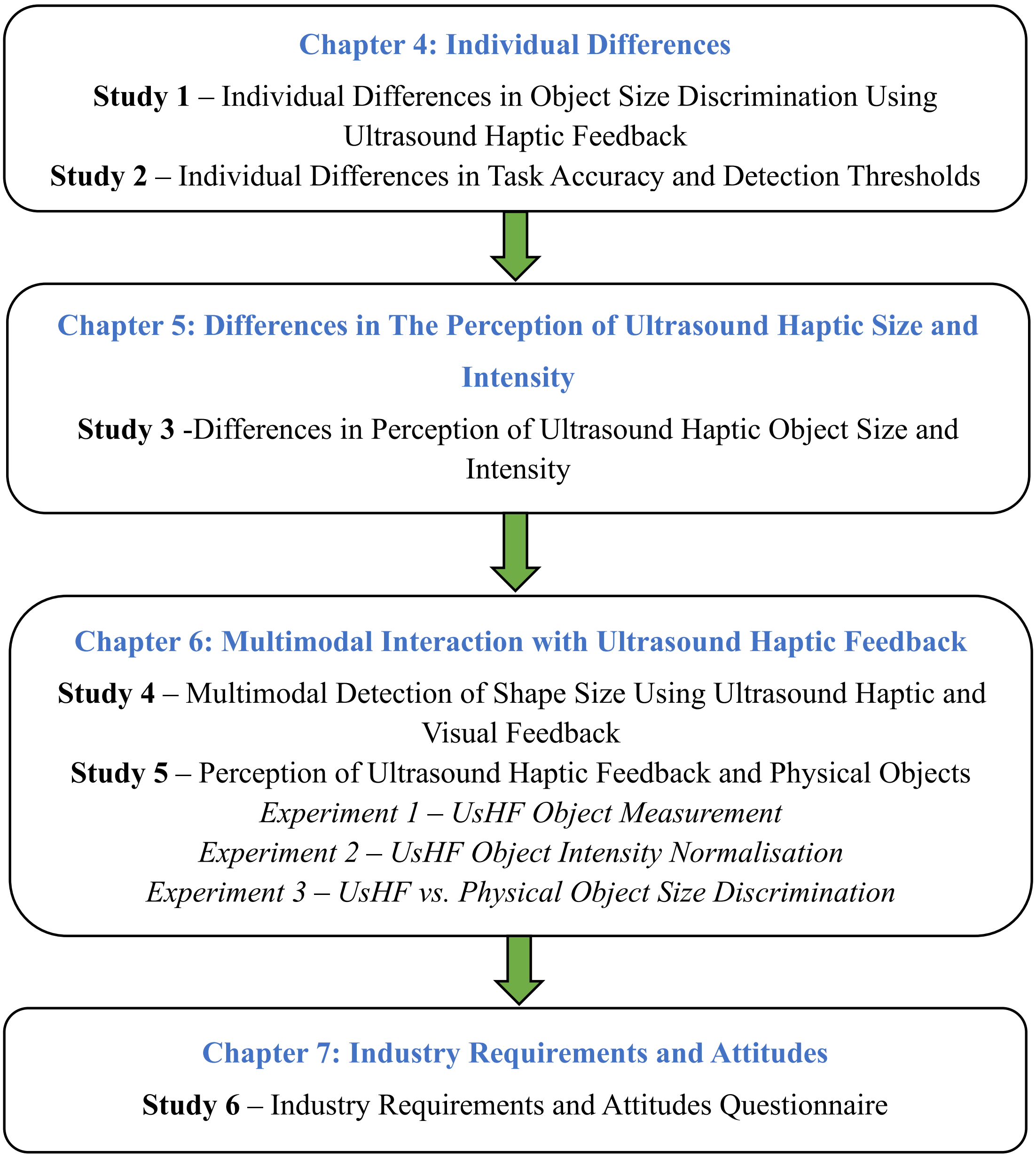


Figure 3-5. An overview of the studies conducted for this research, organised by thesis chapter.

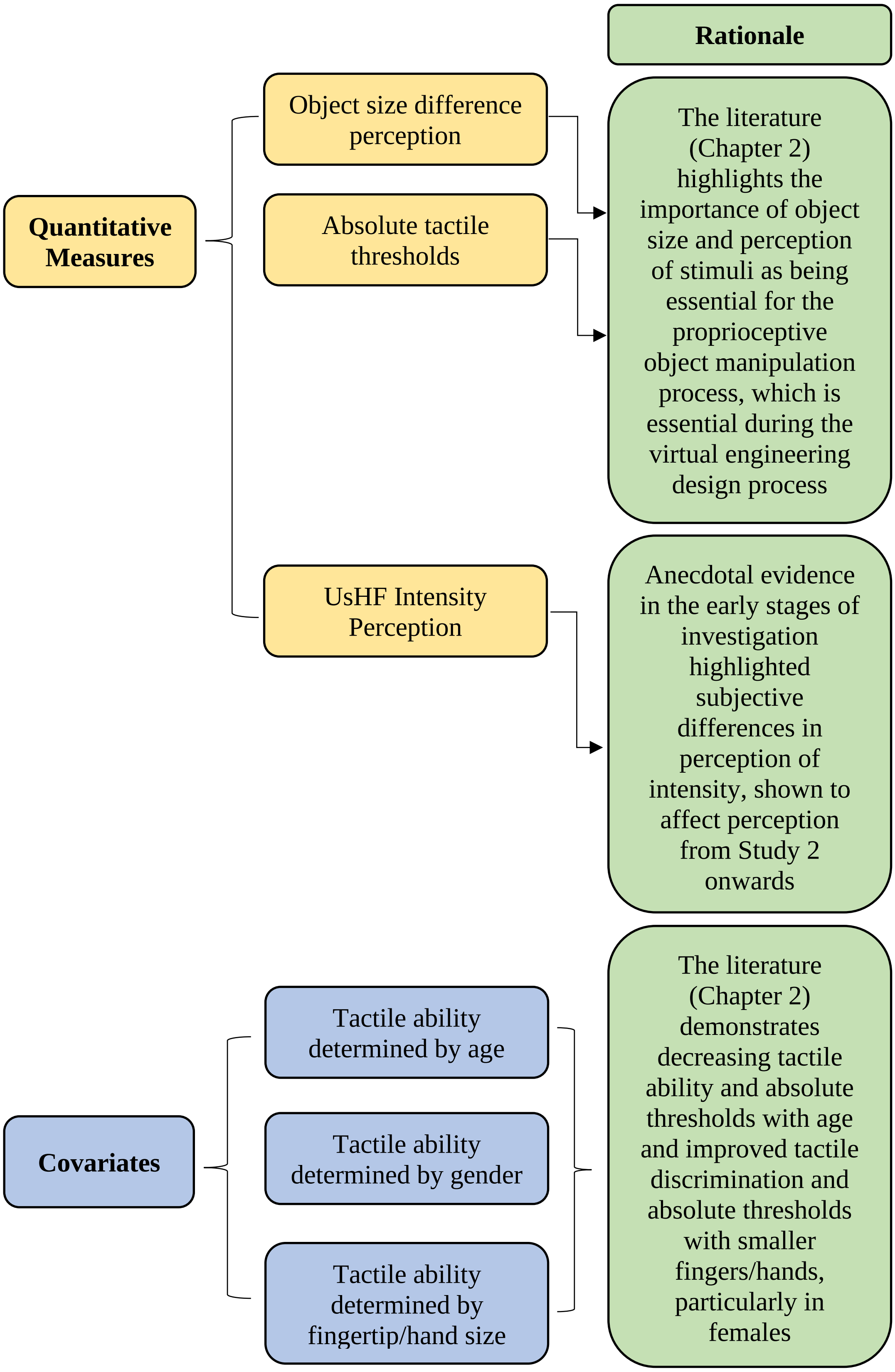
3.2. Research Methods

As both quantitative and qualitative research methods were employed during this PhD, this section will explore these methods below.

3.2.1. Quantitative Experimental Studies (Lab Based)

During the early stages of this PhD, it was clear that foundational research needed to be established before progressing to field-based or application specific investigations, as there too many gaps in the human factors of UsHF knowledgebase to begin with more applied work. This foundational research was achieved through experimental, lab-based study. As there was limited relevant literature available at the time of this PhD's inception, it meant a testing paradigm had to be developed as the work progressed, as is the case when Grounded Theory is applied to quantitative research (Chun Tie, Birks, & Francis, 2019). That being said, some inspiration was drawn from the early UsHF research of Long, Seah, Carter, and Subramanian (2014). For example, in terms of methodology, the aforementioned authors already implemented the use of over-ear headphones playing generic 'white noise' in order to mask the sound the ultrasound array emits when in use. Furthermore, Long, Seah, Carter, and Subramanian (2014) also employed an oil-based method for visualising otherwise invisible UsHF objects which was employed during Study 6 of this PhD.

The adoption of applicable measures is a prudent discussion. The measures employed throughout this PhD can be summarised as: object size differences, absolute tactile thresholds and UsHF intensity perception. Though the first two measures are well documented in the literature exploring human tactile ability (see Chapter 2), the measure pertaining to perception of UsHF intensity was to the author's knowledge, a new and relevant area of investigation which had not been explored before. In all instances these factors were measured on a binary (correct/incorrect) basis. As well as the aforementioned measures, measures of task accuracy were investigated in tandem with measures of individual differences in age, gender and fingertip/hand size in order to determine whether task accuracy was affected by populational differences. Again, these differences in tactile ability are well founded in the literature (see Chapter 2). See *Figure 3.2-1* for a summary of the measures and the rationale for use.



The literature (Chapter 2) highlights the importance of object size and perception of stimuli as being essential for the proprioceptive object manipulation process, which is essential during the virtual engineering design process

Anecdotal evidence in the early stages of investigation highlighted subjective differences in perception of intensity, shown to affect perception from Study 2 onwards

The literature (Chapter 2) demonstrates decreasing tactile ability and absolute thresholds with age and improved tactile discrimination and absolute thresholds with smaller fingers/hands, particularly in females

Figure 3.2-1. Graphic illustrating the qualitative measures, covariates and rationale used during the course of this PhD.

Throughout this research, a choice was made not to use an immersive VR solution, instead, a 2D solution without a head mounted display (HMD) and a user avatar was elected and applied to all quantitative studies. Though this appears to be counterproductive as the research should be relevant for fully immersive VR, there was one primary guiding factor when making this decision. This was the phenomena known as ‘body-based scaling’. Body based scaling refers to how humans obtain object size information based on the known size of their body, particularly the hands (Ogawa, Narumi, & Hirose, 2017). Considering maximum grasping ability of an individual, a practical example can be extracted from this theory wherein the width of an object appears smaller to someone with large hands, and larger to someone with small hands (Linkenauger, Ramenzoni, & Proffitt, 2010). Applied to VEs, similarly, VR object size is underestimated when virtual body size is perceived to be large, and object size is overestimated if body size is perceived to be small (Linkenauger, Ramenzoni, & Proffitt, 2010). Based on the aforementioned evidence, it was deemed the use of avatars within fully immersive VR could introduce uncontrollable variables, thus, convoluting results.

3.2.1.1. Training

During all lab-based studies, basic training was provided to participants which instructed them how to use the UsHF device. For training during studies 1-3, a torus of 57mm in size at 100% intensity was projected above the array. Participants were offered verbal guidance on where best to place their hand to feel the object. They were then allowed 30 seconds to explore the object. Participants were not told what size the object was. During studies 4 and 5, training took the same format using the same stimulus, but was presented in video format due to impaired communication ability between the researcher and participant in the presence of COVID-19 countermeasures.

3.2.2. Qualitative Studies (Questionnaire based)

Due to the COVID-19 pandemic, initial plans to hold workshops and focus groups were unfortunately infeasible (this limitation will be explored in more detail in section 8.5). This restriction meant that unfortunately industry participants did not get the chance to interact with the UsHF technology. However, as a well-founded approach to understanding acceptance and attitudes (Vogelsang, Steinhüser, & Hoppe, 2013), an online questionnaire during Study 6 (Chapter 7), and in-person surveying of participants after using the technology was employed during Study 5 (Section 6.3) for qualitative data collection.

Though established measures, such as the Technology Acceptance Model (TAM) questionnaire were explored, due to the nature of the investigations, it was deemed inapplicable. This was due to the fact that, in one instance (Study 4) participants would not be using the technology, and in the other (Study 6) participants would be experiencing UsHF in a controlled and non-applied atmosphere, and many of the lines of questioning used in the TAM focus on whether the technology improved the user's work/job efficiency, productivity and performance. Though some TAM inquiry into ease of use could conceivably have been applied, most of the original model would have to be edited or completely redacted, thus rendering the model invalid.

Instead, bespoke questionnaires were created in order to establish pertinent areas of application, perceptions of UsHF and VR within engineering design, expectations, requirements, first impressions and so on (see Appendix E and G) for the questionnaires used). The use of these questionnaires highlighted interesting areas of investigation, particularly pertaining to potential applications of UsHF and envisaged obstacles that could prevent seamless integration of the technology into the virtual design workflow (see Studies 4 and 6).

3.3. Quantitative Analysis Methods

Quantitative data were analysed using both parametric and non-parametric tools within IBM SPSS Statistics, as well as descriptive statistics. All data were subject to scrutiny before selection of the analysis type, for example, in terms of outliers, data type, number of conditions etc. Normality was tested using the Shapiro-Wilk test of normality. Considering parametric tests, independent and paired samples T-Test, Pearson correlation and repeated measures ANOVAs were utilised. For non-parametric tests, Friedman ANOVAs were used.

3.4. Qualitative Analysis Methods

Qualitative data analysis during both studies 5 (Section 6.3) and 6 (Chapter 7) was conducted via the use of NVivo and were subject to thematic analysis. This was achieved via coding of long answer questions to establish underlying themes in responses, and the extent to which the themes were relevant. Simple response questions were analysed using graphing techniques within MS Excel and were formatted in a manner relevant to the question subject.

3.5. General Equipment

As the lab-based experiments during this study utilised the same equipment in most instances (with the addition of some equipment where mentioned), it is pertinent to explore the universal equipment in this section to avoid duplication in the methodology sections of individual study reports. This section will explore the equipment used including for fingertip measurement, the UsHF array, and the software.

3.5.1. Vernier Calliper Fingertip Measurement

Though the investigations conducted were not concerned specifically with fingertip size, but overall hand size, fingertip area was calculated as an established indicator of overall hand size. During studies in which participant's index fingertips were measured (Study 1 and 2) a Vernier calliper was used to determine the size of participant's index finger distal phalanx, by measuring from the tip to the distal interphalangeal crease. The width of the distal phalanx was measured at the widest point. Index fingertip area (mm^2) was calculated using these two measurements (see *Figure 3.5-1*). This method was derived from that used by Peters, Hackeman and Goldreich (2009).

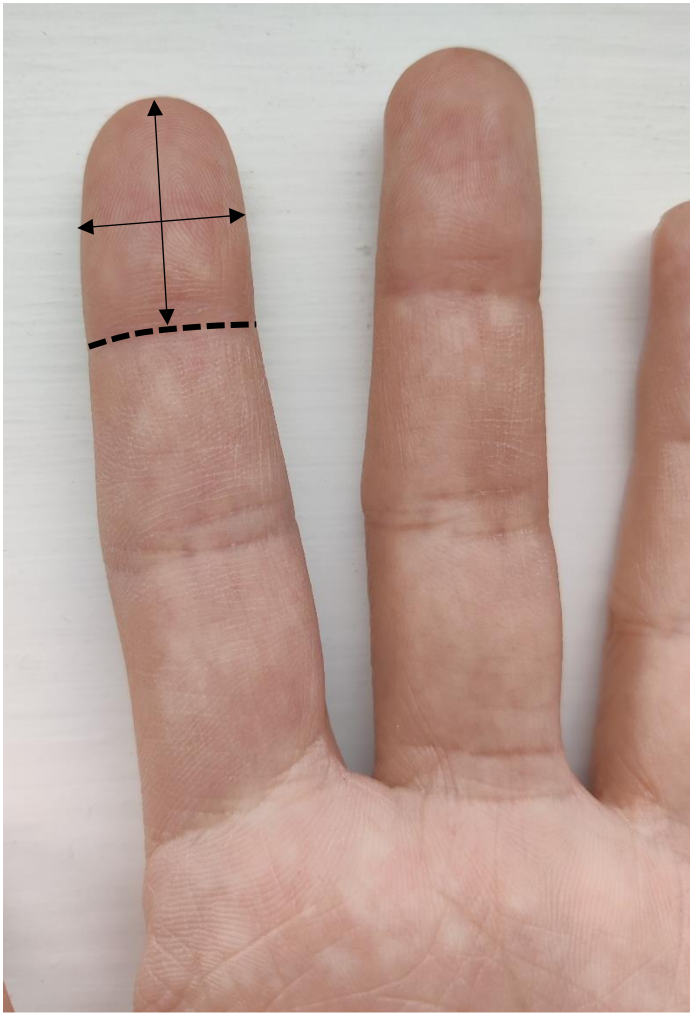


Figure 3.5-1. Illustration of how index fingertips were measured. Dotted line represents the interphalangeal crease and is where the fingertip length was measured to from the tip (represented by vertical arrow). The horizontal arrow represents the width measurement taken at the widest point of the distal phalanx.

3.5.2. The Ultrasound Array

A more in-depth exploration of ultrasound haptics and the technology driving the principle can be found in section 2.6; its specific implementation for this research is described below.

During the present investigations, the ultrasound array used was the Ultrahaptics Evaluation Kit 1 (UHEV1), though the manufacturer is now known as ‘Ultraleap’. The kit consists of the ultrasound array which creates the ultrasound stimuli, and a Leap Motion sensor used for detecting the participant’s hand movements. Hand tracking was not used during any studies; however, the array was set to activate in the presence of the participant’s hand, thus saving power and minimising heat output from the array.

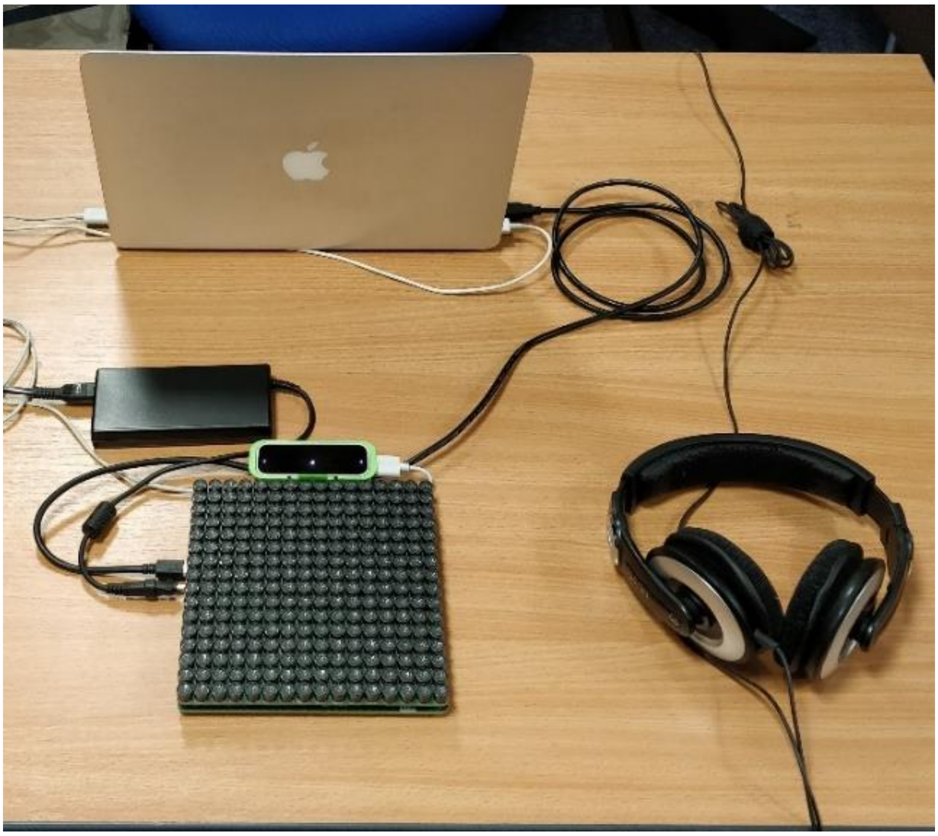


Figure 3.5-2. The UsHF equipment setup from the participant’s location with the ultrasound array closest to them and the researcher’s laptop opposite (left).

The array measures in at 16x16cm and comprises of 245 ultrasonic transducers. The equipment allows for mid-air stimuli to be projected between 5cm and 80cm above the array and can do so with a 60° field of view perpendicular to the array (see *Figure 3.5-2)*. Though it can produce stimuli at a wider field of view, quality is impaired. Beyond this field of view, there will be little haptic sensation, if any.

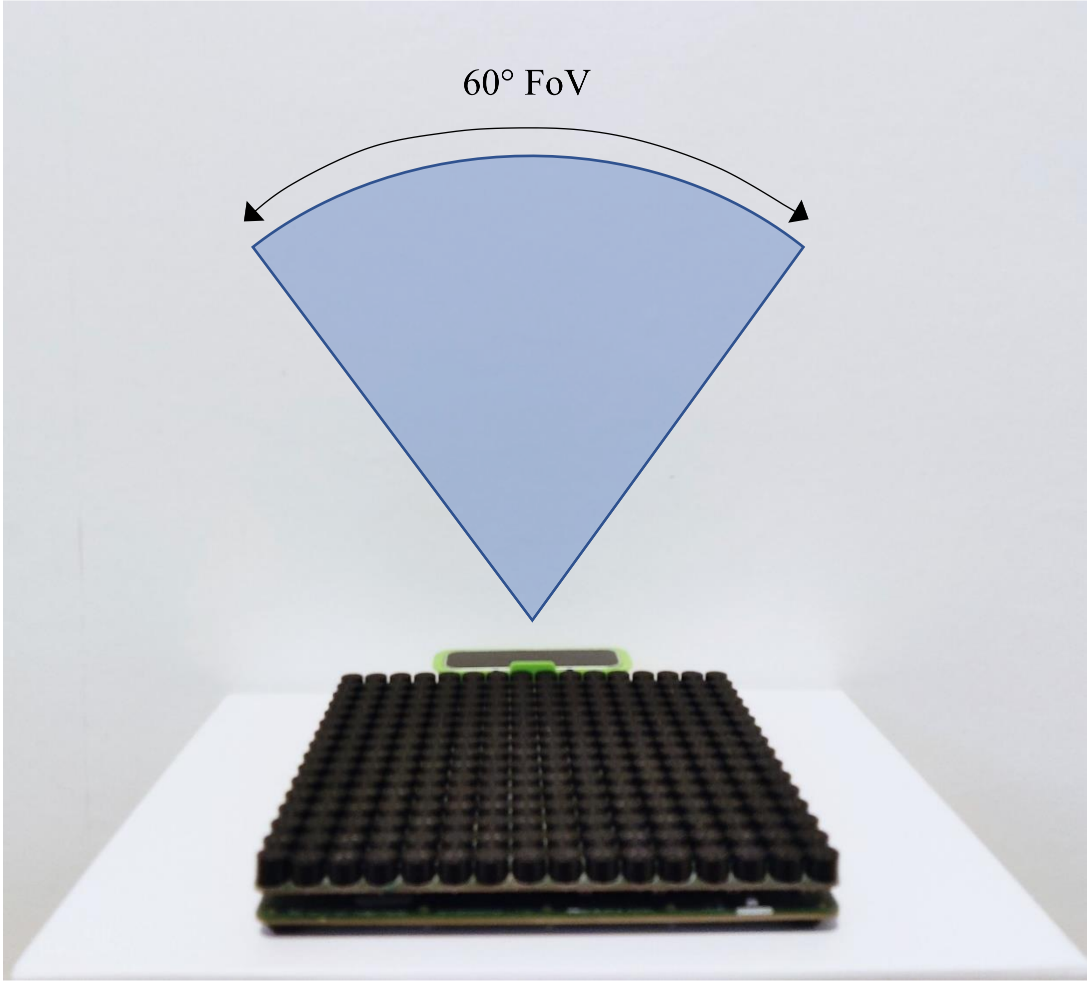


Figure 3.5-3. UHEV1 array mid-air stimuli Field of View (FoV).

The array is also paired with a Leap Motion controller which can detect the presence and location of the user’s hands, as well as gestures. The controller can detect hands effectively at a distance of approximately 60cm but can operate up to a distance of 80cm, albeit with lower accuracy, and does so with a field of view of 140x120°. Furthermore, the Leap Motion controller operates as a frequency of 120Hz. During the present experiments, the Leap Motion controller was only used to activate and deactivate the array when participants’ hands were held over it.

The stimuli produced in all studies was a torus (torus) of varying sizes and intensities. These will be highlighted in the ‘stimuli’ section for each study. See *Figure 3.5-3* for a visual representation of this type of stimulus.

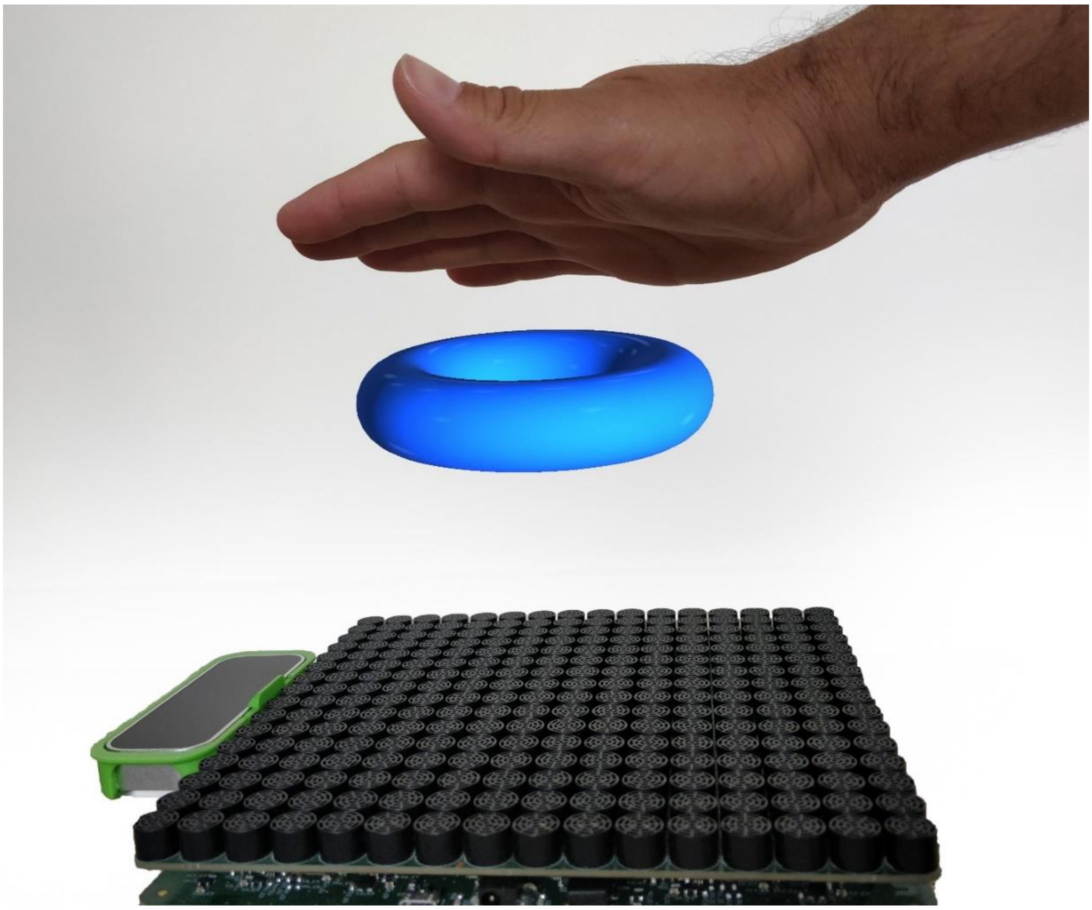
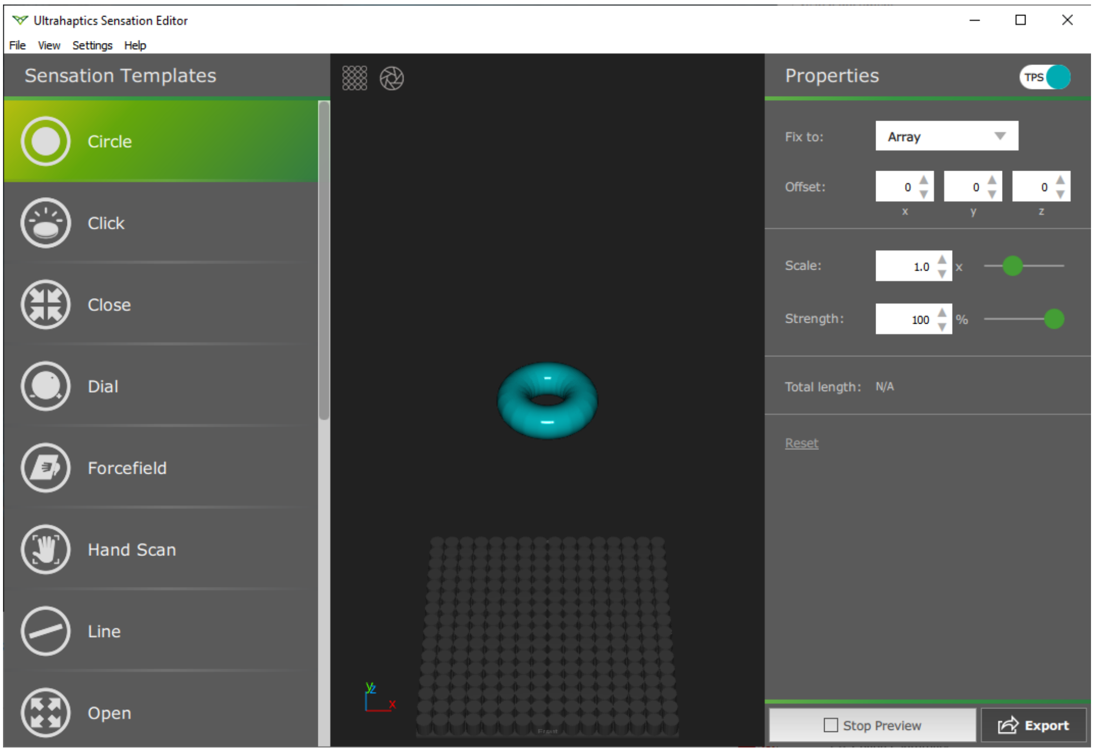


Figure 3.5-4. A visual render of the torus stimulus used throughout all studies.

Over-ear headphones emitting white noise/static were worn by participants in order to mask the noise the ultrasound array makes when activated. Masking the array noise is important because the sounds emitted increase and decrease in volume in tandem with increasing and decreasing mid-air object sizes/intensities.

3.5.3. Software

Throughout this PhD, there has been limited divergence in terms of the software, and thus the outputs used. Though initially this may seem like a limitation, in a practical sense, this allowed for a consistent approach to creating stimuli for the lab-based studies which this thesis explores in later chapters. Indeed, this software was used for all studies involving the ultrasound array. The software used to create stimuli was the Ultrahaptics (now Ultraleap) Sensation Editor (see *Figure 3.5-4*).



Fix to: Array

Offset: 0 (x) 0 (y) 0 (z)

Scale: 1.0 x

Strength: 100 %

Total length: N/A

Figure 3.5-5. The Ultrahaptics (Ultraleap) Sensation Editor which facilitates the customisation of mid-air haptic stimuli.

This tool is simple but allowed the stimuli manipulation required for this PhD. The software package allows the user to select ultrasound objects and manipulate their characteristics, for example, the scale, distance from the array, intensity, and anchor points (palm, array, axis).

3.5.4. Stimuli

The haptic object employed throughout this work was a torus. This shape was selected as while it is three dimensional, there are limited opportunities for users to misinterpret dimensions as they move their hand through the object, unlike, for example, a sphere which would feel larger towards the centre when moving the hand through the object. Utilising other objects during this research would have introduced more variability in how users place and move their hands while interacting with UsHF objects.

Though the software used (see Section 3.5.3) illustrates object size as "X", research conducted during Study 5 (Section 6.3.2) established a method to convert the software scale to a real world, absolute value in millimetres (mm). As this is essential for understanding object sizes used throughout this work, this information has been included in Table 3.5-1 below and will be referred to during studies in which it is relevant.

Table 3.5-1. *Chart illustrating conversion of object size from software value (X) to absolute value (mm) of the Outer Diameter.*

UsHF Object Size Conversion

UsHF Size	Real World OD (mm)	UsHF Size	Real World OD (mm)
0.2x	18	**1.4x**	54
0.3x	21	**1.5x**	57
0.4x	24	**1.6x**	60
0.5x	27	**1.7x**	63
0.6x	30	**1.8x**	66
0.7x	33	**1.9x**	69
0.8x	36	**2.0x**	72
0.9x	39	**2.1x**	75
1.0x	42	**2.2x**	78
1.1x	45	**2.3x**	81
1.2x	48	**2.4x**	84
1.3x	51	**2.5x**	87

Object size was the focus of much of this work, and was such due to the importance of object size perception in both the physical and virtual worlds (see Section 2.2.4).

3.6. Chapter Summary

This chapter explored the universal equipment and software used during this PhD. It also highlights how the ultrasound array works in tandem with the aforementioned software and gives an idea of some of the possibilities that the technology affords, along with some of the limitations of the current setup (FoV, power, range, etc.). Experimental and qualitative research methods were explored to aid understanding on the procedures used as well as their foundation. Furthermore, both the quantitative and qualitative research and analysis methods were also explored, highlighting the research paradigm that was developed for testing UsHF.

Chapter 4: Individual Differences

4.1. Chapter Overview

The previous literature (Chapter 2) showed that prior research into sense of touch indicates that individual differences play a role in the accurate detection of tactile stimuli, but this has not yet been studied in UsHF applications. Specifically, this chapter explores subjective differences in perception of UsHF as a result of individual differences in age, gender, and hand size, with an emphasis on how these differences affect tactile acuity. The chapter also presents the testing paradigm which forms the basis for the experimental work throughout the rest of this thesis.

This chapter includes two studies of individual differences, focussing on whether individual differences in gender, age and hand size affect participants' ability to discern differences in UsHF object size (Section 4.2), as well as perception of UsHF intensity and absolute tactile thresholds (Section 4.3). Study 1 (Section 4.2) not only answered relevant questions in relation to UsHF, but also served as a proof of concept for the aforementioned testing paradigm.

4.2. **Study 1** – Individual Differences in Object Size Discrimination Using Ultrasound Haptic Feedback

4.2.1. Introduction and Rationale (Study 1)

With differences in individual's biology, it is possible that the receptors located within the glabrous skin on the palms and fingers could be subject to individual differences. Research has shown age to be a potential determinant of these differences, whereby tactile thresholds increase significantly with age, particularly when detecting smaller stimuli on the fingertips between the ages of 12 and 50 (Thornbury & Mistretta, 1981; Tremblay & Master, 2015). Finger size and gender have also been noted as a determinant of tactile acuity, due to varying densities of Meissner's corpuscles in particular, which are responsible for the perception of light-touch and have been shown to decrease as a function of both age and finger size (Dillon, Haynes, & Henneberg, 2001). Both gender and finger size appear to be intertwined in terms of effect on tactile sensitivity, as females statistically have smaller fingers than their male counterparts

(Peters, Hackeman, & Goldreich, 2009). Furthermore, it is possible that there are psychophysical differences in the perception of UsHF.

Based on the aforementioned literature, there is a clear basis for the existence of individual differences in tactile abilities. However, there is no literature investigating the impact of such differences in the context of UsHF. Despite the lack of literature, it was possible to predict that the individual differences present for tactile perception of physical objects would also be present during the use of artificial haptic feedback and indeed, UsHF, the primary focus of this investigation. Thus, it was hypothesised that ability to perceive differences would correlate with individual differences in age, gender and fingertip/hand size.

This study served not only as a proof of concept for a UsHF testing paradigm that incorporates measures (size difference perception) of tactile acuity relevant to virtual engineering design, but also as a measure to understand individual differences in use of UsHF.

4.2.2. Method (Study 1)

The experimental method for the current study is outlined in the following sections.

Participants

The experimental method for the current study is outlined in the following sections.

Participants

30 participants (15 male, 15 female, *N* = 30) comprising of students and staff from the University of Nottingham were recruited. The mean age for the male group was (*M* = 32.73, *SD* = 8.75) and the female group (*M* = 31.8, *SD* = 10.22). Participants were required to verify their suitability for the study by confirming they had no impairments that prevented normal use of their hands or their ability to detect tactile stimuli. Participants were paid a £5 Amazon voucher for taking part.

Equipment

For a summary of the equipment used, see Section 3.3, general equipment.

The array was set to 100% intensity throughout the investigation. For a summary of the forms used during this study, see Appendix A.

Stimuli

Details of the stimuli used during each condition can be found in Table 4.2-1

Table 4.2-1. *A summary of all the stimuli pairs used during Study 1. 24 object pairs were repeated once for a total of 24 pairs.*

Pair Number	Object Sizes	Pair Number	Object Sizes
1	18mm vs. 87mm	**13**	18mm vs. 87mm
2	33mm vs. 72mm	**14**	27mm vs. 78mm
3	27mm vs. 78mm	**15**	33mm vs. 72mm
4	39mm vs. 66mm	**16**	21mm vs. 84mm
5	42mm vs. 63mm	**17**	48mm vs. 57mm
6	51mm vs. 54mm	**18**	45mm vs. 60mm
7	30mm vs. 75mm	**19**	36mm vs. 69mm
8	45mm vs. 60mm	**20**	30mm vs. 75mm
9	21mm vs. 84mm	**21**	39mm vs. 66mm
10	24mm vs. 81mm	**22**	42mm vs. 63mm
11	48mm vs. 57mm	**23**	51mm vs. 54mm
12	36mm vs. 69mm	**24**	24mm vs. 81mm

This trial utilised a torus shape, the attribute of the shape that changed was the size, from 18mm to 87mm scale created within the Ultrahaptics Sensation Editor. Pair numbers were randomised in their presentation to participants. Each participant experienced the same, randomised pair order. Object sizes were collated so the size difference gradually decreased. For example, paired shape size differences incrementally reduced from 18mm and 87mm, to 51mm and 54mm.

Study Design

The present study utilised a within-subjects design. The task was to feel tori pairs of different sizes and discern which was larger of the two. All participants took part in the same trials and were exposed to them in the same, randomised order. In total, the study consisted of a training period to acclimatise participants to the sensation of UsHF, followed by the primary trial, within which there were 24 shape pairs. The two shapes from each pair were projected into mid-air individually. Participants were given up to 30 seconds to feel each shape using only their dominant hand. Ethical clearance to conduct this study was granted by the University of Nottingham, Faculty of Engineering ethics committee.

Procedure

Participants were asked to read and understand the study brief, at which point they were asked to provide their consent to take part, along with their age, gender and dominant hand. Fingertip measurements were also taken. Participants were reminded at this point the dominant hand they specified would be the only hand they were to use throughout the study. Participants were asked to put on the headphones and confirm whether they could hear the white noise being played. White noise was played at a volume which masked the sound of the ultrasound array but not the researcher's voice. Participants were allowed a training period, in which they had the opportunity to feel a shape in mid-air so they were familiar with the sensation of UsHF (see Section 3.2.1.1).

During the trial, participants were asked to determine the largest of a pair of two tori of different sizes projected within mid-air. Participants were aware of which shape (number) they were feeling via verbal prompts throughout the trial. Participants explored the first shape then moved their hand away from the array whilst the second shape was projected, they then felt the second shape and made their judgement on which was largest by placing a tick in the corresponding box on the answer sheet. Participants reported their answer by placing a tick in the relevant box on the answer sheet.

4.2.3. Results (Study 1)

Initially, correct answers were plotted against trial number in order to visualise the effect decreasing object size differences had on the number of correct answers.

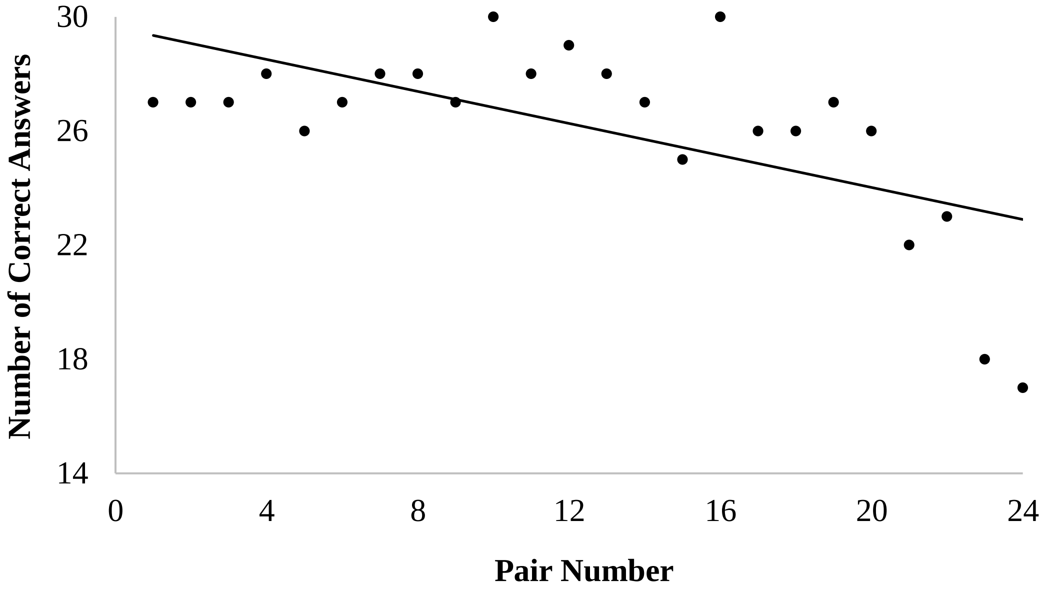


Figure 4.2-1. Scatter plot showing how many participants (of 30) answered correctly by object pair. For this graph, pairs were ordered from 18 vs. 87mm (1) to 51 vs. 54mm 24).

Figure 4.2-1 illustrates a degradation in the number of correct responses from 30 participants as the shape size differences became smaller and harder to discern. This is particularly apparent for the two smallest shape size differences (48mm vs. 57mm and 51mm vs. 54mm), in which only 22, 23, 18 and 17 of 30 participants gave the correct answer, albeit with no individual differences predicting lower accuracy.

Beginning to investigate individual differences, individual index fingertip areas were plotted with gender to establish whether there was any basis for the suggestion that males have larger fingers and thus, overall hand size when compared to females.

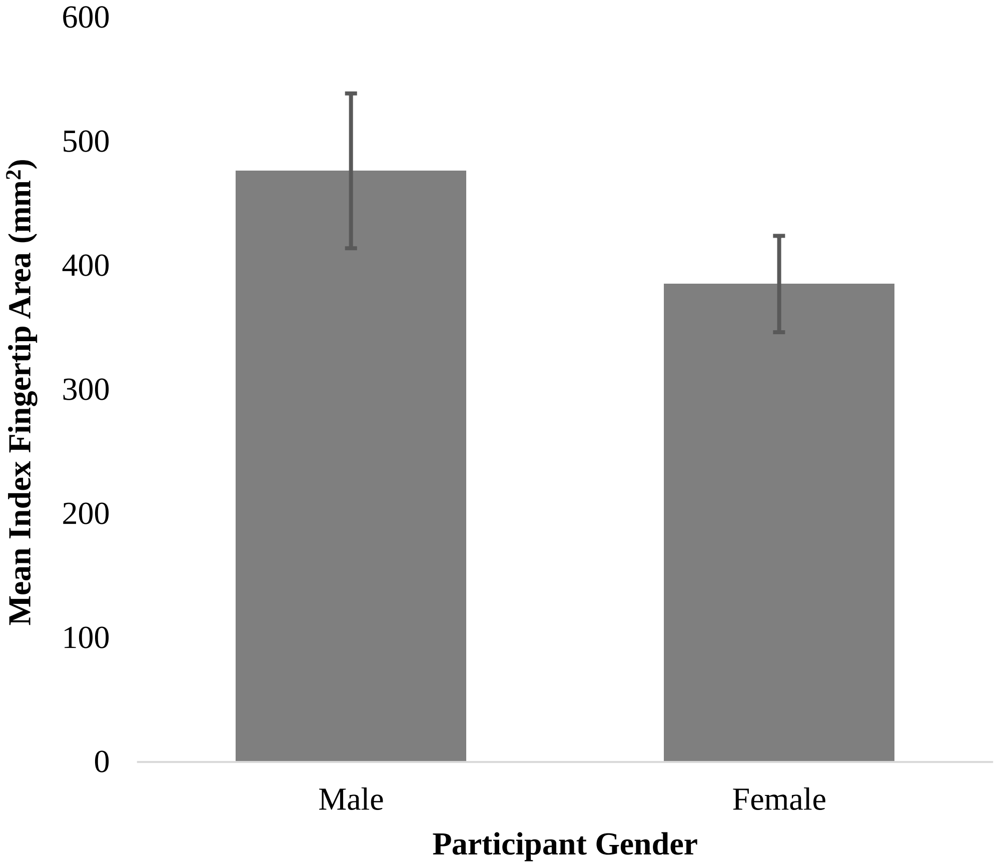


Figure 4.2-2. Shows mean index fingertip area measurements (mm^2) for male and female participants. Error bars: Standard deviation.

Figure 4.2-2 illustrates larger mean index fingertip areas for male participants. This observation is validated by an independent samples T-Test which shows a significant difference between index fingertip area sizes in males (*M* = 47.65, SD = 6.45) compared to females (*M* = 38.51, SD = 4.03), t(28) = 4.66, *p* < .000.

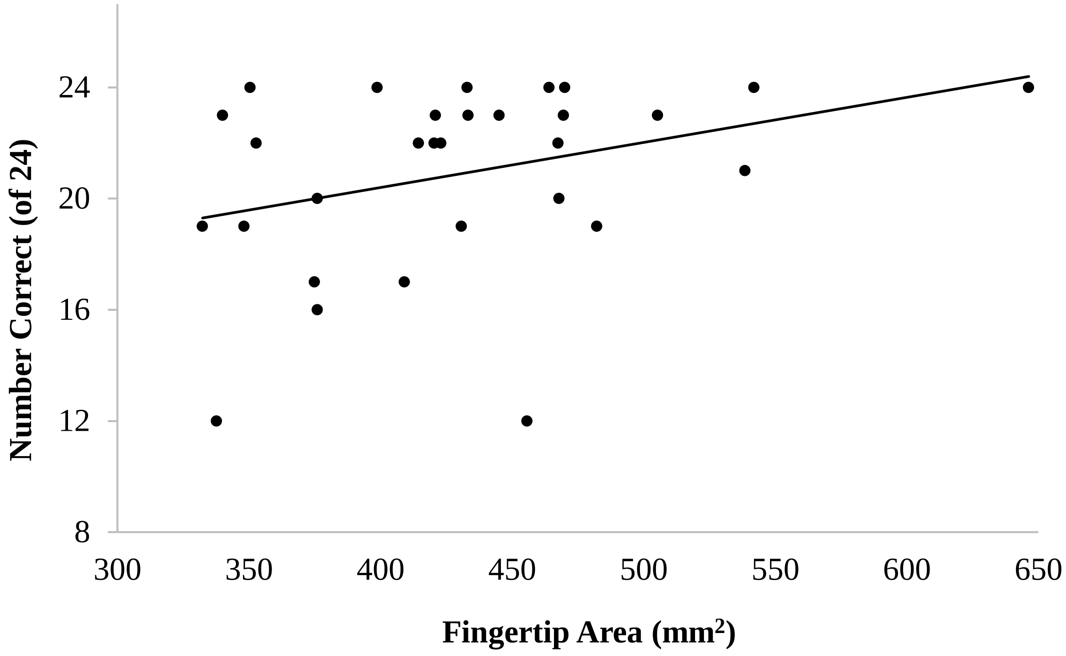


Figure 4.2-3. Shows the mean total correct answers plotted against fingertip area (mm^2) with line of best fit

Figure 4.2-3 indicates the presence of a positive correlation between the mean number of correct answers with increasing fingertip area. However, conducting a Pearson correlation test revealed no significant correlation between fingertip area and mean number of correct answers, r = .338, n = 30, *p* = .068.

An independent samples T-Test was conducted to compare the mean number of correct responses for two groups, males and females. There was no significant difference in the number of correct responses between males (*M* = 21.00, *SD* = 3.61) and females (*M* = 20.80, *SD* = 3.23), t(28) = .160, *p* = .874.

A Pearson correlation was conducted in order to establish whether age was a determinant of task accuracy. No relationship between age and the number of correct answers was found, r = .175, *N* = 30, *p* = .355.

4.2.4. Discussion (Study 1)

Individual differences in age, gender and fingertip/hand size were not found to be a determinant of accuracy on the current shape size discrimination task using UsHF. Research suggests the presence of hand and finger size differences between genders, whereby on average, males have larger hands and fingers than females (e.g., Dillon et al., 2001; Peters et al., 2009). These differences were observed presently and suggest the correlation between fingertip size and the density of Meissner's corpuscles witnessed by Dillon et al. (2001) also to be present. Furthermore, the assumption was made that the degradation of the aforementioned mechanoreceptors as a function of age would also be present, as witnessed during other investigations (e.g., Thornbury & Mistretta, 1981; Tremblay & Master, 2015). As mentioned earlier, the mechanoreceptors located in the fingertips, specifically Meissner's corpuscles which are essential for tactile feedback, particularly when detecting light stimulation, though Pacinian corpuscles are also said to be essential for the perception of UsHF (Rakkolainen, Freeman, Sand, Raisamo, & Brewster, 2020).

Despite establishing participant's finger sizes differed significantly between males and females in the current sample (*Figure 4.2-2),* the difference in mean number of correct answers between genders, did not. Contrary to previous investigations (e.g., Dillon et al., 2001; Peters et al., 2009), smaller fingers and thus a higher density of Meissner's corpuscles did not yield more accurate detection of object size differences. Conversely, in fact, *Figure 4.2-3* shows that those with a larger fingertip area and thus, less densely concentrated cutaneous mechanoreceptors at the fingertips were more likely to answer accurately, albeit without significant correlation. Finally in terms of individual differences, there was no reduction in task accuracy as age increased, suggesting age did not determine overall accuracy when discerning shape size differences. What was visible, was a universal degradation in accuracy with decreasing size differences (*Figure 4.2-1*), the implications of which will be addressed later in this section.

The current results do not support previous findings which utilised different methods of tactile stimulation. It is possible to speculate about the current findings on several levels. It is conceivable that the basis for the investigation, that is the variations in densities of Meissner's corpuscles as a function of age and finger size (and thus gender), does not have an impact on ultrasound haptic applications. This could be due to the relatively low frequency response (30-50Hz) of Meissner's corpuscles (although still within the range of the equipment used for this study). Instead, it is possible that Pacinian corpuscles are more relevant for the sensing of ultrasound haptic feedback, as they are more sensitive to higher frequency stimulation (250-350Hz) (Purves et al., 2001). That being said, Pacinian corpuscles and sensitivity to vibrotactile stimuli has still been shown to decrease with age (Verrillo, 1980).

Focussing on the ultrasound technology, it is plausible that individual differences were not present due to the intensity level used during trials. It is possible to speculate that UsHF would become harder to detect as intensity decreases and age and hand sizes increase. It is also possible that positive correlation between hand size and performance seen in *Figure 4.2-3* was due to the task used. It could be speculated that those with a larger hand size required less exploration of the haptic shapes and thus, were more suited to detecting variation from a stationary and less varied hand position. Whereas individuals with smaller hands were required to move their hand to explore shape boundaries in order to determine size, thus losing a central point of reference.

While these issues are worthy of further investigation in subsequent studies, the current investigation also highlighted some practical implications. Looking back to *Figure 4.2-1* it is possible to see a sharp decline in task accuracy when the difference between shape size pairs reduces from 18mm vs. 45mm (a difference of 27mm) to 51mm vs. 54mm (a difference of 3mm). Although this only represents a reduction in size difference of 15mm, it accounted for a 41% decline in the accurate recognition of shape size differences. This has practical implications for a number of sectors, particularly for design and engineering applications, for which accuracy is of primary concern. These data should be considered within the aforementioned application areas and serve to advise against the use of UsHF for displaying similar shapes when the difference in size falls below 15mm.

As the degradation of tactile acuity as a function of age, gender and mechanoreceptor densities is a well-documented phenomenon (e.g., Dillon et al., 2001; Peters et al., 2009; Thornbury & Mistretta, 1981; Tremblay & Master, 2015), it is unclear why evidence for this was not observed during the present investigation. The most plausible explanation is that the intensity of the ultrasound was too high to illicit any visible differences in tactile abilities. Future investigations should explore the same individual determinants of tactile ability whilst adding ultrasound intensity as a variable. This future proposal should assess both the practical implication of a change in ultrasound intensity in task form, and also a functional test of individual tactile thresholds when using ultrasound haptic feedback.

4.2.5. Conclusion (Study 1)

As the inaugural study for this PhD, it has granted valuable knowledge on populational differences of UsHF perception. Though well-founded differences in tactile abilities were not found during this study, an indication of the potential limitations in size discrimination ability were witnessed (*Figure 4.2-1*), which offers valuable data in understanding the limitations of UsHF, as well as aiding the research direction of this PhD. Future research should seek to further explore limitations in object size discrimination whilst aiming to understand how intensity impacts populational differences in tactile ability and general perception of mid-air stimuli.

4.3. **Study 2 –** Individual Differences in Task Accuracy and Detection Thresholds

4.3.1. Introduction and Rationale (Study 2)

Despite aforementioned evidence emphasising the benefits haptic feedback can have on interaction with virtual environments (Section 2.4.2-3 & Chapter 2.5), research in the field of somesthesis highlights some limitations of individual perception of tactile information that could affect detection of synthetic haptics. For example, Wickremaratchi and Llewelyn (2006) summarise several studies demonstrating that increasing age leads to increased tactile thresholds, increased vibration detection thresholds and declining spatial acuity of touch. Peters et al. (2009) also report increased tactile acuity in females and individuals with smaller hands. These differences could have implications for accurate and effective use of UsHF within many potential applications, particularly within the field of engineering design, in which engineers require virtual renditions of designs to be as accurate as possible in order to replace relevant design stages, such as physical prototyping.

Study 1 (Section 4.2) sought to investigate individual differences in an object size discrimination task. The investigation yielded insignificant results and determined that individual differences were not a predictor of UsHF object size discrimination, but raised further queries about differences in detecting UsHF at various intensities, this investigation aimed to address those queries. The aforementioned study utilised UsHF at a fixed, 100% intensity, thus possibly not highlighting individual differences when considering theorised and observed examples of higher tactile sensitivity of females, those with smaller hands (e.g., Dillon, Haynes, & Henneberg, 2001; Peters et al, 2009) and decreasing tactile acuity with increasing age (e.g., Wickremaratchi & Llewelyn, 2006). To investigate this query further, a shape size discrimination task was created in order establish potential differences in individual size discrimination ability as tactile cues became increasingly difficult to detect. A task to determine individual's absolute tactile detection threshold using UsHF was also devised, thus further investigating some variables and aiming to understand the absolute limit of UsHF detection in the tested population.

Based on the current literature and findings from Study 1 (Section 4.2), two hypotheses were proposed. Firstly, there would be a difference in error rate between genders, fingertip/hand size and age groups during the shape size discrimination task. Secondly, there would be a difference in absolute tactile threshold as a function of gender, fingertip/hand size and age.

4.3.2. Shape Size Discrimination Task (Part 1)

4.3.2.1. Method – Study 2, Part 1

The experimental method used for part 1 of study 2 is outlined in the following sections.

Participants (Part 1)

16 male and 14 female (*N* = 30) participants were recruited on a voluntary basis. The mean age for males was (*M* = 30.6, *SD* = 8.32) and females (*M* = 29, *SD* = 5.74). Participants were required to verify their suitability for the study by confirming they had no impairments that prevented normal use of their hands or their ability to detect tactile stimuli. As such, all participants had normal use of their hands and normal tactile abilities. Participants were paid a £5 Amazon voucher for taking part.

Equipment (Part 1)

For a summary of the equipment used, see Section 3.3, general equipment. For a summary of the forms used during this study, see Appendix B.

Stimuli (Part 1)

The shapes projected into mid-air were a torus at varied sizes and intensities, starting at 18mm and increasing to 87mm in 3mm increments, see Table 4.3-1 for a summary of stimuli used.

Table 4.3-1. *This table illustrates the size of shape pairs used during three conditions. The stimuli size/difference combinations were the same during all conditions, but intensity (indicated by the column header) changed in each condition. Table shows randomised order for each condition.*

Condition		
C1 (80% Intensity)	**C2 (60% Intensity)**	**C3 (40% Intensity)**
72mm vs. 33mm	69mm vs. 36mm	78mm vs. 27mm
66mm vs. 39mm	72mm vs. 33mm	66mm vs. 39mm
63mm vs. 42mm	84mm vs. 21mm	81mm vs. 24mm
60mm vs. 45mm	75mm vs. 30mm	69mm vs. 36mm
81mm vs. 24mm	87mm vs. 18mm	84mm vs. 21mm
87mm vs. 18mm	78mm vs. 27mm	75mm vs. 30mm
54mm vs. 51mm	63mm vs. 42mm	54mm vs. 51mm
57mm vs. 48mm	57mm vs. 48mm	60mm vs. 45mm
84mm vs. 21mm	81mm vs. 24mm	57mm vs. 48mm
69mm vs. 36mm	60mm vs. 45mm	87mm vs. 18mm
75mm vs. 30mm	54mm vs. 51mm	63mm vs. 42mm
78mm vs. 27mm	66mm vs. 39mm	72mm vs. 33mm

Object pairs were collated so the size difference gradually decreased. For example, paired shape size differences incrementally reduced from 18mm and 87mm, to 51mm and 54mm. There were 3 conditions; 1 (80%), 2 (60%) and 3 (40%) intensity, within which objects were projected at different intensities indicated by the percentage figure. There were 12 shape size pairs per condition, for a total of 36 object pairs. Object pairs were randomised during each condition, meaning the order of the pairs were different in each condition.

Study Design (Part 1)

The study utilised a within-subjects design. The task was to discern which object in a pair of tori was largest. All participants took part in three conditions (mentioned in Table 4.3-1) in the same. The order in which participants took part in each condition was counterbalanced. Participants were given a training period so they could acclimatise to the sensation of UsHF (see Section 3.2.1.1). Participants received no visual stimuli during their interaction with UsHF, and instead relied on haptic feedback alone.

Procedure (Part 1)

Participants were asked to read and understand the study brief, at which point they were asked to provide their consent to take part, along with their age, gender and dominant hand. Fingertip measurements were also taken. Participants were reminded at this point the dominant hand they specified would be the only hand they were to use throughout the study. Participants were asked to put on the headphones and confirm whether they could hear the white noise being played. White noise was played at a volume which masked the sound of the ultrasound array but not the researcher’s voice. Participants were allowed a training period, in which they had the opportunity to feel a shape in mid-air so they were familiar with the sensation of UsHF (see Section 3.2.1.1). Participants received verbal prompts to notify them which shape (number) they were interacting with. Participants were presented with one object of the pair at a time, they could feel each shape for up to 30 seconds. Participants explored the first shape then moved their hand away from the array whilst the second shape was projected, they then felt the second shape and made their judgement on which was largest by placing a tick in the corresponding box on the answer sheet. Participants used this method for all three conditions (1-80%, 2-60% and 3-40%).

4.3.2.2. Results - Study 2, Part 1

Results in this section will be split into two parts to separate the shape size discrimination task and the absolute threshold task that participants completed.

Part one of the analysis is concerned with analysing factors affecting the accurate detection of shape size differences during three conditions (80%, 60% and 40% intensity).

Conducting an independent samples T-Test revealed that Male participants had significantly larger index fingertip area (M = 481.58, SD = 41.98) (mm^2) than Female participants (M = 386.57, SD = 39.66) (mm^2), t = (28) = 6.35, p = <.001.

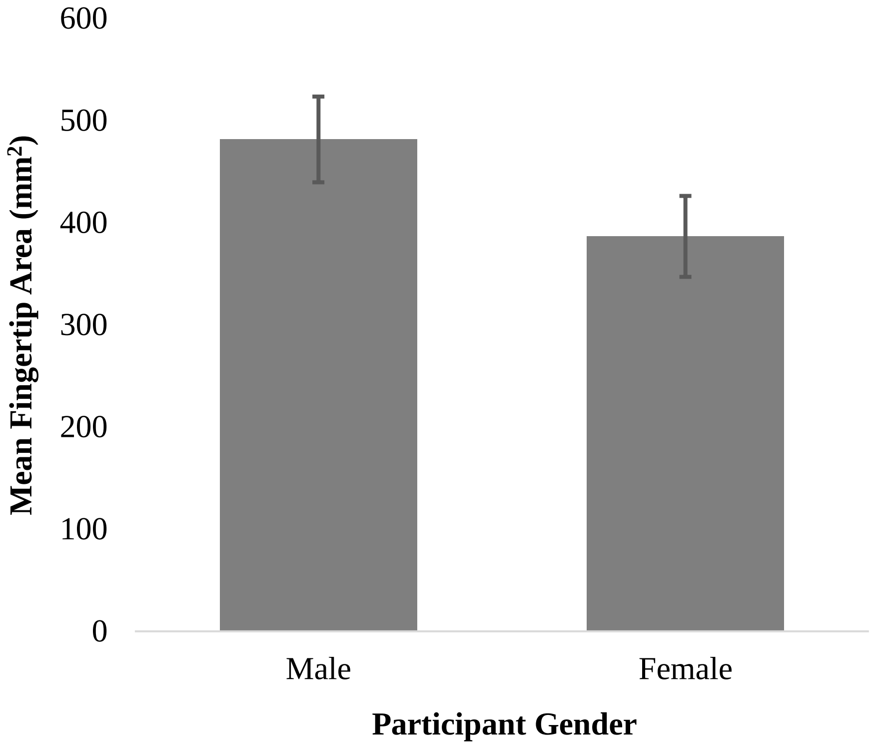


Figure 4.3-1. Bar chart showing mean dominant hand index fingertip area for male and female participants. Error bars: 95% CI.

Figure 4.3-1. Illustrates the significantly larger index fingertip area of male participants compared to female, suggesting the relevant tactile receptors for the current task are arranged more densely in females than males.

In order to understand whether a specific variable is responsible for the decline in accuracy during the present shape size discrimination task, the data were subject to analysis via a Repeated Measures ANOVA. Mauchly's test indicated that the assumption of sphericity had been violated $X^2(2) = 13.25$, $p = .001$, as such, degrees of freedom were corrected using Greenhouse-Geissser estimates of sphericity ($\varepsilon = .65$). The results show mid-air object intensity had a significant effect on the number of correct answers, $F(1.3, 23.36) = 7.16$, $p = .009$. The number of correct answers decreased as mid-air object intensity decreased from 80% ($M = 11.29$) to 60% ($M = 10.41$) to 40% ($M = 7.12$). Pairwise comparisons revealed the reduction in the number of correct answers when mid-air object intensity decreased from 80% to 40% (4.17, 95% CI [6.70, 1.64]) was significant $p = .001$, as well as the decrease from 60% to 40% (3.29, 95% CI [6.07, 0.51]), $p = .018$. However, the decrease in number of correct answers between 80% and 60% intensity (0.88, 95% CI [2.09, -0.32] was not significant $p = .208$. These significant results are represented in *Figure 4.3-2* and *4.3-3*.

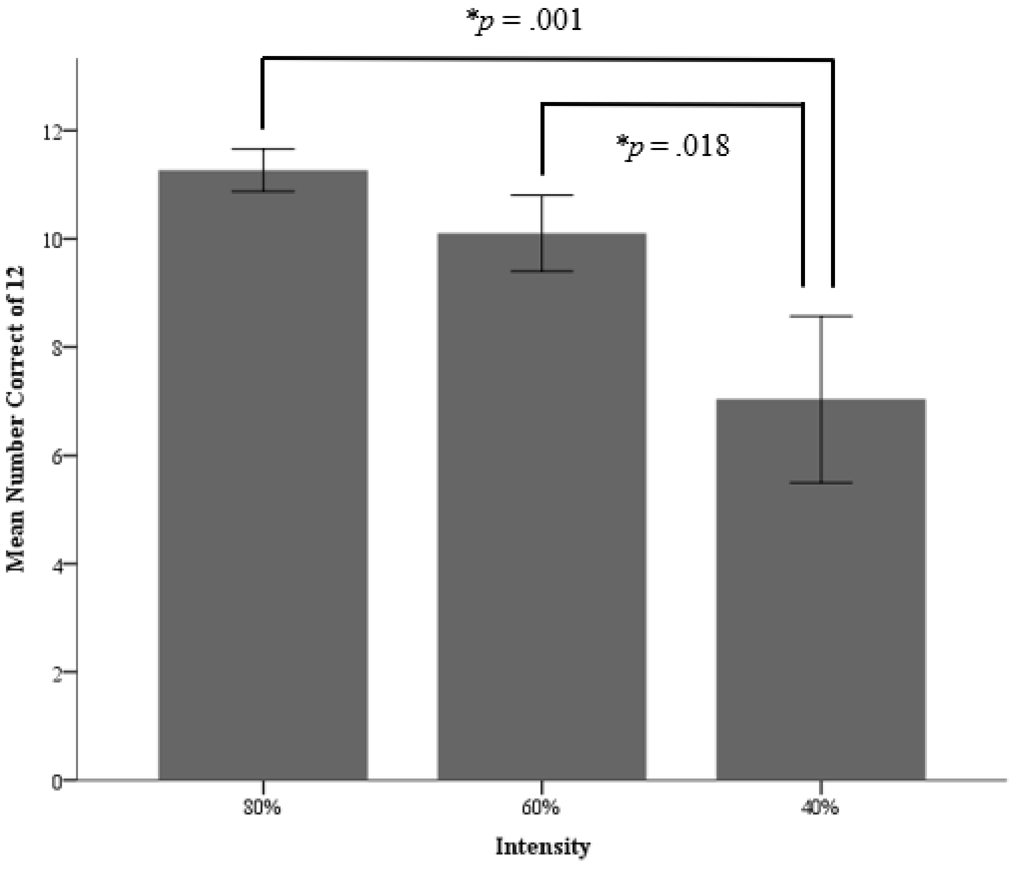


Figure 4.3-2. Bar chart showing mean number of correct responses (of 12 shape pairs) per intensity condition. Error bars: 95% CI.

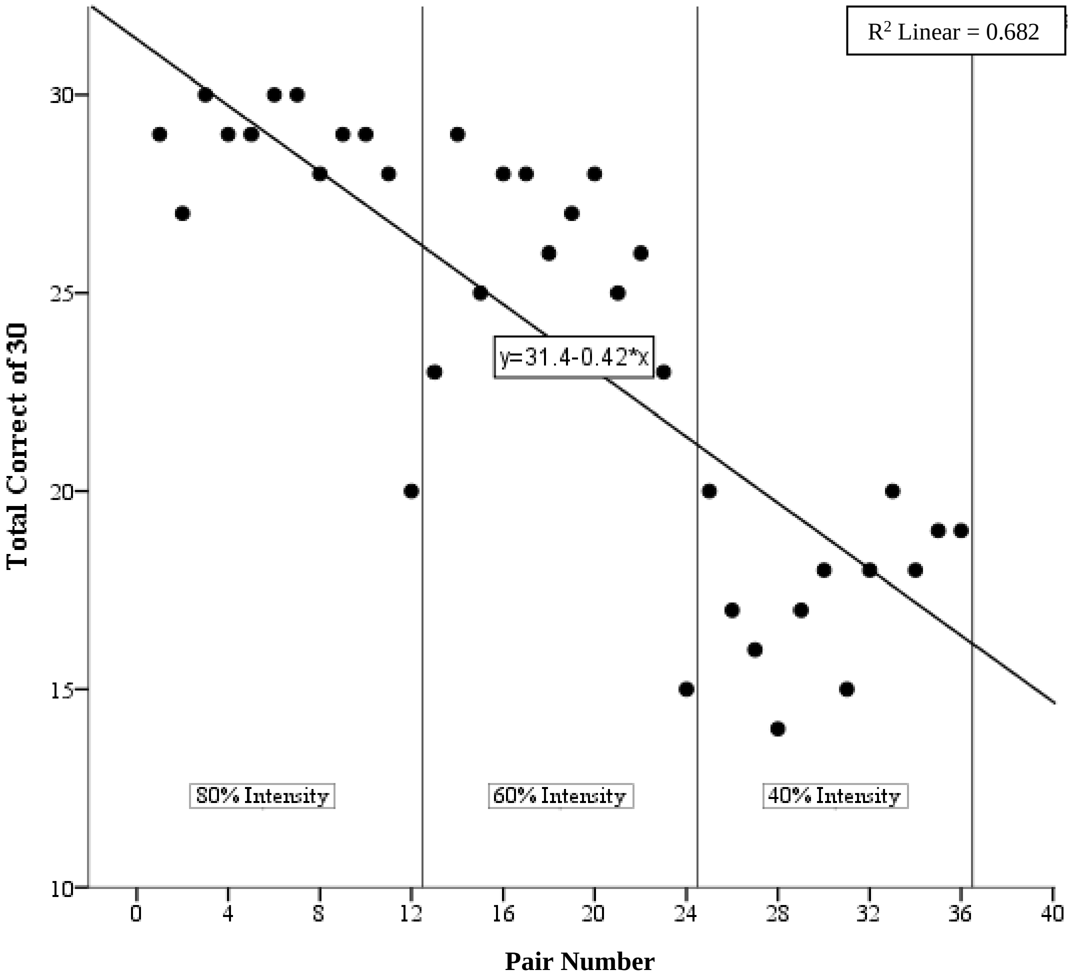


Figure 4.3-3. Scatter plot with fit line demonstrating decreasing number of correct answers for 30 participants as size differences and intensity decreased (left to right) increased. Dividers are present highlighting the intensity condition (12 data points per condition).

Figure 4.3-2 and *Figure 4.3-3* demonstrate the prevalence of lessened ability to discriminate shape size differences accurately as the intensity of mid-air shapes decreases.

There was no significant effect of gender on the number of correct results in any of the conditions *F*(1.30, 23.36) = .96, *p* = .362, of age on the number of correct results in each condition *F*(3.89, 23.36) = .99, *p* = .489 or of fingertip area on the number of correct results in each condition *F*(2.60, 23.36) = 2.64, *p* = .080. As no significant differences were found, post-hoc analyses were not conducted. These results suggest the variables of gender, age and fingertip area had no significant effect on the number of correct answers given when provided during the shape size discrimination task at different intensities.

In order to highlight the presence of any potential practice effects, whereby task performance would improve based on the actual order participants completed the counterbalanced intensity conditions, a Pearson correlation was used to analyse the number of correct answers in each condition based on order, not intensity. There was no correlation between the condition order and the number of correct answers (*r* = -.191, *n* = 90, *p* = .26). The descriptive statistics (mean and standard error) are shown in *Figure 4.3-4*.

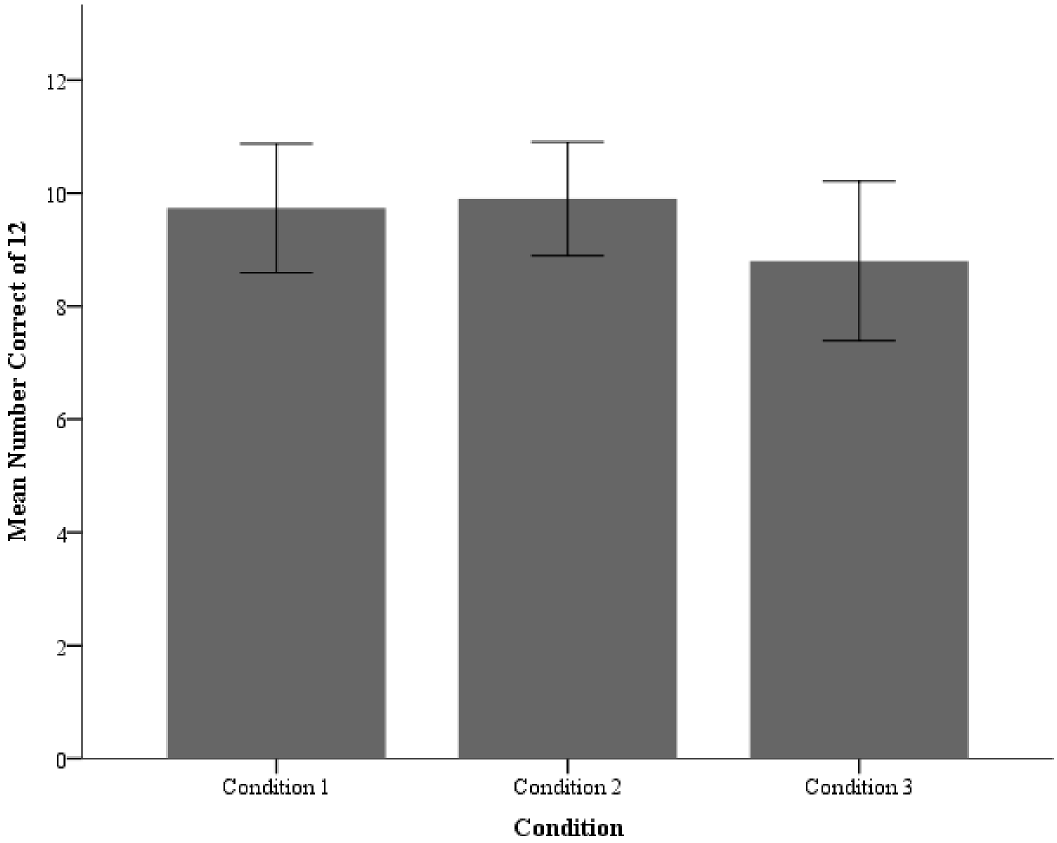


Figure 4.3-4. Bar chart showing mean number of correct answers (of 12 shape pairs) for the actual order participants experienced them.

4.3.3. Absolute Threshold Task (Part 2)

This section focusses on the method and results section from part 2 of study 2, which examined individual differences in absolute tactile thresholds.

4.3.3.1. Method – Study 2, Part 2

This section will explore the methodology employed for part 2 of study 2.

Participants (Part 2)

The same group of participants used in part 1 were used in part 2. See Section 4.3.2.1.

Equipment (Part 2)

For a summary of the equipment used, see Section 3.3, general equipment. For a summary of the forms used during this study, see Appendix B.

Stimuli (Part 2)

During Part 2, testing absolute tactile thresholds of participants was conducted. A torus at 57mm scale was projected at different intensities. The intensity decreased from 100% in 5% increments. See the following section which outlines how the stimuli were manipulated based on participant response.

Study Design

This study used a within-subjects design. The intention of this study was to establish limitations of tactile detection while using UsHF. During Part 2 of the investigation, absolute tactile thresholds were measured. Participants were tasked with identifying the presence of mid-air UsHF sensations. In order to do this, a torus of 57mm in size was projected at varied intensities. Initially the object was presented at 100% intensity which was varied in 5% increments. The object size did not change.

Procedure (Part 2)

Participants were asked to put on the headphones and confirm whether they could hear the white noise being played. White noise was played at a volume which masked the sound of the ultrasound array but not the researcher's voice.

The participant was initially provided with a torus of 57mm in size at 100% intensity. The participant would report whether they could feel the stimulus or not. If they could feel the stimulus, the intensity of it was then decreased in 5% increments until the participant could no longer feel it. When the intensity decreased to a level the participant could no longer identify the stimulus, the intensity was increased to the previously detected intensity. When/if the object was detected, the intensity was decreased again. For example, if the stimulus was detected at 40% but not 35%, the next stimulus would be displayed at 40%. If the participant could not feel the stimulus at 40% intensity, it would be increased by another 5% increment until it was felt again, then reduced once more until the participant could no longer feel it. The last time the object was felt was then recorded. This method prevented any demand characteristics that could have manifested during the test.

4.3.3.2. Results – Study 2, Part 2

Part two of the analysis is concerned with factors affecting the absolute threshold of UsHF detection.

A Three-way ANOVA was conducted in order to establish whether three independent variables, gender, age and index fingertip area had a significant effect on the minimum detectable UsHF intensity. There was homogeneity of variances as assessed by Levene’s test for equality of variances, $p = .106$. There were no statistically significant interactions between gender, age and fingertip area on the minimum detectable UsHF thresholds.

Table 4.3-2. *Table showing Three-Way ANOVA output analysing interactions between three independent variables (age, gender and fingertip area) on one dependent variable (object size discrimination accuracy). No significant main effects or interactions were present.*

Dependent Variable: Minimum Detected Intensity (%)

Source	df	F	Sig.
Gender	1	.015	.905
Age_Group	3	.792	.514
Fingertip_Area_Group	2	3.166	.066
Gender*Age_Group	1	.148	.705
Gender*Fingertip_Area_Group	1	.474	.500
Age_Group*Fingertip_Area_Group	3	.239	.868
Gender*Age_Group*Fingertip_Area_Group	0	-	-

Results from the three-way ANOVA seen in Table 4.3-2 suggest the variables of gender, age and fingertip area had no significant effect on the absolute threshold of participants when using UsHF. The average absolute threshold for all participants was M = 30.16%, the average for females M = 28.21% and for males M = 31.88%.

4.3.4. Discussion (Study 2)

The current investigation sought to establish whether three individual differences in gender, age, and dominant hand index fingertip area (as an indicator of hand size) had an effect on participants' ability to correctly distinguish differences in shape sizes projected into mid-air using Ultrasound Haptic Feedback (UsHF), and whether the aforementioned variables had an impact on participant's UsHF absolute detection threshold. Using the current analysis methods, it can be concluded that there were no significant effects of the specified individual differences on the number of correct responses, or the absolute (lowest) detection threshold.

However, there are some observations that are worth discussing. As expected, there was a correlation between decreasing intensity and shape size differences and the number of correct responses, as seen in *Figure 4.3-3* and *Figure 4.3-4*. This observation was further demonstrated during the repeated measures ANOVA, in which there was a significant reduction in the number of correct answers when object intensity was reduced to 40%. The presence of this effect should be considered for applications in which accurate rendition of shape sizes is important, in which stimuli should be projected at an intensity no lower than 60%. As expected, Male participants had significantly larger index fingertip areas, and thus, larger hand size when compared to Female participants, suggesting Females had a higher density of both Meissner's and Pacinian corpuscles. However, the data do not suggest this to be a significant indicator of task accuracy or absolute tactile thresholds as hypothesised (e.g., Dillon et al., 2001; Peters et al., 2009; Wickremaratchi & Llewelyn, 2006).

Anecdotal evidence collected from trial participants suggested that a characteristic of UsHF is that the larger shape of a pair projected at the same intensity can subjectively feel less intense than the smaller shape. This could have implications for the accurate detection of shape size differences. Anecdotal evidence collected from 18 participants during the present investigation suggests this unintentional feature was used to their advantage during the task, in which they learnt they could circumvent the haptic exploration process usually associated with object exploration, and instead receive size cues from the perceived higher or lower intensity of a particular shape of a pair. It is clear from the results in this paper that this phenomenon is not warping the data completely, as a decline in task accuracy can be seen to correlate with decreasing ultrasound intensity. However, if most participants are circumventing the haptic exploration process and basing their responses in the shape size discrimination task on more obvious prompts, such as the decreasing perceived intensity with larger object size, it is possible task results would be different.

If indeed this phenomenon is borne out in future studies, it could have implications for applications of UsHF. It could be hypothesised that when intensity is normalised to feel the same for all object sizes, intensity ques that inform on size could disappear, giving rise to aforementioned individual differences in size discrimination that were expected. It is also plausible that the data would look similar to those seen in this experiment, which would have implications in itself. In the event the latter hypothesis is borne out, in that even with normalised intensities there are no individual differences in size discrimination ability, it could mean that UsHF intensity and rendered object size are factors that need not be designed for, to a point (40%), alluding to simpler implementation at the development stage, and a population that does not require a user experience tailored to them. Furthermore, future results along these lines could also have implications for the engineering design field, wherein accurate object rendering using UsHF may be unnecessary, with users relying on other, simpler cues such as higher or lower intensity stimuli, leading to faster and more intuitive use. A further investigation should seek to understand whether intensity is indeed utilised by participants to understand object characteristics in place of exploration. Finally, it should aim to understand what implications results of either nature have for implementations of UsHF for VR and engineering design.

4.3.5. Conclusion (Study 2)

Based on the current size discrimination task, it can be concluded that individual differences in age, gender and hand size did not have a significant effect on task accuracy across all three intensities. It can also be concluded that the aforementioned measures of individual differences did not have a significant effect on absolute (minimum) UsHF detection thresholds. However, Study 2 established an understanding of how UsHF intensity can affect perception of object size differences, specifically that objects displayed at lower intensities, in this instance 40% intensity, significantly affects size discrimination accuracy. Furthermore, this research received feedback from a significant number of participants stating that objects with large size differences *felt* different, not in terms of size, but intensity and, how those size differences were easy to detect and explore as a result. This phenomenon should be explored in greater detail in order to understand the underlying mechanisms behind perception of intensity and how it can be used to affect interpretation of mid-air object size.

4.4. Chapter Summary

The rationale for this chapter was based heavily on the existing literature on haptic feedback and the sense of touch (Chapter 2). As such, the two studies within this chapter sought to determine whether existing principles and knowledge pertaining to individual differences in the sense of touch can be applied to UsHF. It was important to ascertain this, as failure to do so could have resulted in these variables affecting appropriate and effective implementations of UsHF for engineering design. During Study 1 it was determined that the existing knowledge of the sense of touch could not be generalised to UsHF, as the data demonstrated no individual differences in UsHF size discrimination but did raise important questions which aided the research direction, including, insight into how UsHF intensity might play an important role in how users perceive object size. Study 1 (Section 4.2) also aided understanding of limitations in size discrimination ability, highlighting that accuracy declined significantly when objects varied in size by ~21mm and less.

Study 2 highlighted a number of interesting findings, establishing limitations in accurate size discrimination at different UsHF intensities, giving an initial indication of how intensity can affect size discrimination accuracy. This study established a significant decrease in size discrimination accuracy at 40% intensity compared to both 80% and 60%. Despite establishing the role intensity plays in task accuracy, there were no individual differences identified during the size discrimination task or absolute (minimum) UsHF detection threshold task. However, an absolute UsHF threshold of approximately 30% intensity was established for all the entire participant pool.

Despite not replicating the individual differences established in the literature during these studies, this means that there are less likely to be confounding variables during future research and applications of UsHF. Indeed, the research in this chapter helped create foundational research into the nuances of UsHF and provided a clear research direction towards establishing the effect UsHF intensity has on object perception. Therefore, on the basis of these studies, it was concluded that there is no evidence to suggest individual differences play a role in perception of UsHF size differences, but that further work is needed to understand the role of mid-air object intensity.

Chapter 5: Differences in Perception of Ultrasound Haptic Object Size and Intensity

5.1. Chapter Overview

The research presented in Chapter 4 found no evidence for a role of individual differences in perception of UsHF, but there was anecdotal evidence that object intensity could be important. Thus, UsHF intensity, and how it affects perception of mid-air object size is explored further in this chapter. To do this, a study was conducted in which the size-intensity combinations of mid-air objects are manipulated. In doing so it is hoped that the data will determine the elements of UsHF that affect perception of object size, and indeed how best to minimise and potentially correct for the inconsistencies in how mid-air objects are delivered to the user.

5.2. Introduction and Rationale (Study 3)

Anecdotal evidence from studies 1 and 2 (Section 4.2 and 4.3) indicated a tendency for participants to prioritise perceived object size cues from subjective differences in object intensity, as opposed to object size. This comes as the technology fails to project mid-air objects of different sizes at a subjectively consistent intensity level. As such, larger objects were almost always perceived as being projected at a lower intensity than their smaller counterparts. Whilst this effect can potentially be compensated for at a software level by increasing larger and decreasing smaller object intensities so the perceived difference is normalised, the phenomenon raises important questions as to whether intensity and not size can be manipulated to affect perception of object size.

For example, it is plausible that users of UsHF do not need to experience accurate rendition of object sizes and can instead receive size cues from varied object intensities instead. Though this speculation is not founded in the literature, there are works which suggest the presence of simple haptic feedback can affect perception of virtual objects. A study conducted by Abdullah, Lawson, & Roper (2017), demonstrates that haptic feedback need only be given on the wrist of users to signify collision of the fingertips with virtual objects. On a similar note, research by Son and Park (2018) found that simple cutaneous tactile feedback to the palm could improve perception of large virtual objects. This suggests the mere presence of haptic feedback not directly analogous to the virtual object, can be enough to improve user's perception of virtual objects.

A finding like this could afford simpler implementations of UsHF, saving time at the development stage by reducing the complexity of programming. This would be achieved in several ways. Initially, the process of creating an accurate scale of how virtual objects should be represented using UsHF, both in terms of dimensions and intensity, would be significantly reduced. An undertaking like scaling UsHF object size and intensity would require a significant amount of user testing on subjective interpretation of individual and specific objects. More complex shapes would also require a larger and higher fidelity ultrasound array to render the objects. Furthermore, the time taken to create the software in accordance with a complex dataset from scaling investigations would be significantly reduced if users simply require a haptic cue, hypothetically in the form of a short burst of UsHF of varying intensity as a size cue, rather than a full render of an object.

In order to satisfy one of the primary aims of the current PhD research, which is to understand the human factors issues surrounding UsHF, the aim of this investigation was to establish whether UsHF intensity has an effect on the accurate detection of mid-air object size. As such, the aim of this study has direct implications for understanding the use of UsHF for engineering applications. It was hypothesised that if participants are receiving conflicting object size cues from varied intensity, that the first pair of conditions (1 and 2) in which object sizes remained consistent but intensity varied, should yield the lowest number of correct results. The second pair of conditions (3 and 4) included larger objects at higher intensities, and smaller objects at lower intensities. These conditions were chosen based on anecdotal evidence from previous studies and served as a primitive normalisation of subjective experience of object intensity, making smaller objects feel the same intensity as larger ones by reducing the intensity of the smaller objects. It was hypothesised that conditions 3 and 4 would see relatively high scores if people could accurately discern object sizes, and moderate scores if intensity affects the comprehension of object size at all and low scores if individuals were only receiving object sizes cues from the intensity level and not the actual object dimensions. Finally, conditions 5 and 6 included larger objects at lower intensities and smaller objects at higher intensities. These were created in order to exacerbate anecdotal findings from previous studies, during which when objects were projected at the same intensity, the larger objects were reported to feel (subjectively) less intense. Average scores were expected due to individuals interpreting conflicting size/intensity information differently.

5.3. Method (Study 3)

The experimental method for the present study will be outlined in the following four sections.

Participants

15 males and 15 females (*N* = 30) took part on a voluntary basis. The mean age of male participants was (*M* = 30, *SD* = 9.49) and female was (*M* = 26, *SD* = 2.90) with an age range of 22-59. 11 Participants had experience using UsHF before, whilst 19 participants had no experience using UsHF. Participants were required to verify their suitability for the study by confirming they had no impairments that prevented normal use of their hands or their ability to detect tactile stimuli. Participants were paid a £10 Amazon voucher for taking part.

Stimuli

Details of the stimuli used during each condition can be found in Table 5-1.

Table 5-1. *Table showing the size and intensity of the shape stimuli, their combinations for six conditions and order with examples. Pair order during all conditions was randomised and experienced by all participants in the same, randomised order. "%" refers to object intensity.*

Condition	Object Size Combinations		Example
SameSize80% (1)	78mm vs. 78mm 66mm vs. 66mm 54mm Vs 54mm	42mm Vs 42mm 30mm Vs 30mm 18mm vs. 18mm	42mm (100%) vs. 42mm (80%)
SameSize60% (2)	54mm Vs 54mm 78mm vs. 78mm 66mm vs. 66mm	30mm Vs 30mm 18mm vs. 18mm 42mm Vs 42mm	66mm (100%) vs. 66mm (60%)
Smaller80% (3)	84mm vs. 18mm 78mm Vs 24mm 72mm vs. 30mm	66mm Vs 36mm 60mm vs. 42mm 54mm Vs 48mm	72mm (100%) vs. 30mm (80%)
Smaller60% (4)	78mm Vs 24mm 84mm vs. 18mm 60mm vs. 42mm	72mm vs. 30mm 54mm Vs 48mm 66mm Vs 36mm	54mm (100%) vs. 48mm (60%)
Larger80% (5)	66mm Vs 36mm 72mm vs. 30mm 54mm Vs 48mm	78mm Vs 24mm 60mm vs. 42mm 84mm vs. 18mm	24mm (100%) vs. 78mm (80%)
Larger60% (6)	72mm vs. 30mm 54mm Vs 48mm 84mm vs. 18mm	66mm Vs 36mm 78mm Vs 24mm 60mm vs. 42mm	42mm (100%) vs. 60mm (60%)

All stimuli used were a torus shape. When looking at Table 5-1, it can be seen that the stimuli used during condition 1 and 2 are slightly different to those used during conditions 3-6. The object dimensions during condition 1 and 2 decrease in 24mm increments, whereas they decrease in 18mm increments during the remaining conditions. This is for a number of reasons. As the pairs of stimuli during condition 1 and 2 are of the same size, a smaller number of individual shape sizes were required (6 vs. 12). The 12 shape dimensions used in conditions 3-6 were established from studies 1 & 2 (Chapter 4) as being within the optimal range for detection by participants. In order to remain in the optimal shape size range whilst maintaining the same number of shape pairs (6) during condition 1 and 2, the increments had to be increased from 18mm to 24mm. Although the difference is relatively negligible in practice, this means pair combinations from condition 1 and 2 are not directly comparable to those found in conditions 3-6. However, as the stimuli in condition 1 and 2 remain in the optimal range, the overall results can be compared reliably.

During conditions 1 and 2, shapes were projected at the same size. During condition 1, one shape remained at 100% intensity and the other at 80%. Condition 2 saw the lower intensity object projected at 60%. During conditions in which shape dimensions were different (3-6), the same shape sizes were used, albeit in different size/intensity/order combinations. During condition 3 and 4, the smaller shape was projected at a lower intensity (80%, condition 3 and 60%, condition 4). The larger shape remained at 100%. Finally, during conditions 5 and 6 the larger shape was of lower intensity than the smaller shape (80%, condition 5 and 60%, condition 6). See *Figure 5-1* for an illustration of stimuli.

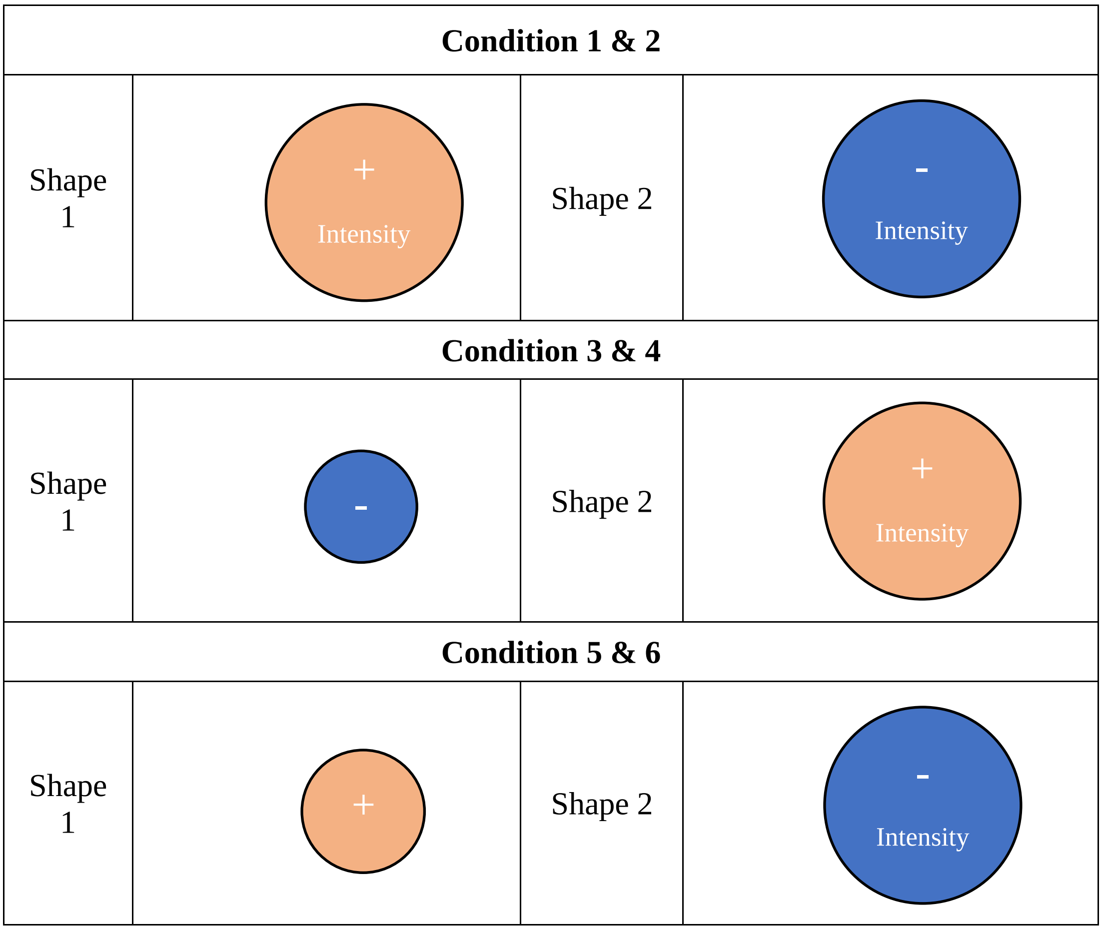


Figure 5-1. Visual illustration of the shape size/intensity combinations for each condition. The orange circle showing a "+" signifies the shape being projected at 100% intensity. The blue circles with a '-' represent shapes projected at a lower intensity. Physical differences in size of the circles depict whether the object is larger or smaller than the previous/following object.

Study Design

The study utilised a within-subjects design comprising of 6 conditions. Each condition used different combinations and variations of shape size/intensity and in the results section, will be referred to as SameSize80% (Condition 1), SameSize60% (Condition 2), Smaller80% (Condition 3), Smaller60% (Condition 4), Larger80% (Condition 5) and Larger60% (Condition 6). Conditions were not presented as separate entities but were representative of different shape size/intensity combinations, randomised during one trial in order to prevent practice effects. Participants experienced shape pairs in the same, randomised order. Participants experienced 6 unique shape size/intensity combinations during 6 conditions, for a total of 36 object pairs. As such, the number of correct answers was marked out of 36.

Procedure

Participants read the brief and completed the consent form before taking part. Participants provided demographic information including their age, gender and dominant hand, they were also asked to state whether they had used UsHF before. Participants were asked to put on the headphones and confirm whether they could hear the white noise being played. White noise was played at a volume which masked the sound of the ultrasound array but not the researcher's voice. Participants were then given a training period (see Section 3.2.1.1). After exploring the trial shape, participants began judging shape size differences. Participants received verbal prompts to notify them which shape (number) they were interacting with. Participants were presented with one object of the pair at a time, they could feel each shape for up to 30 seconds. Participants explored the first shape then moved their hand away from the array whilst the second shape was projected, they then felt the second shape and made their judgement on which was largest by placing a tick in the corresponding box on the answer sheet. If they believed the shapes to be of the same dimensions, they placed a tick in the "No Difference" box on the answer sheet.

5.4. Results (Study 3)

In order to establish whether the condition influenced the number of correct answers given, the data were first subject to inspection for outliers to determine which analysis was appropriate. Construction and examination of a box plot shown in *Figure 5*-2, identified several outliers.

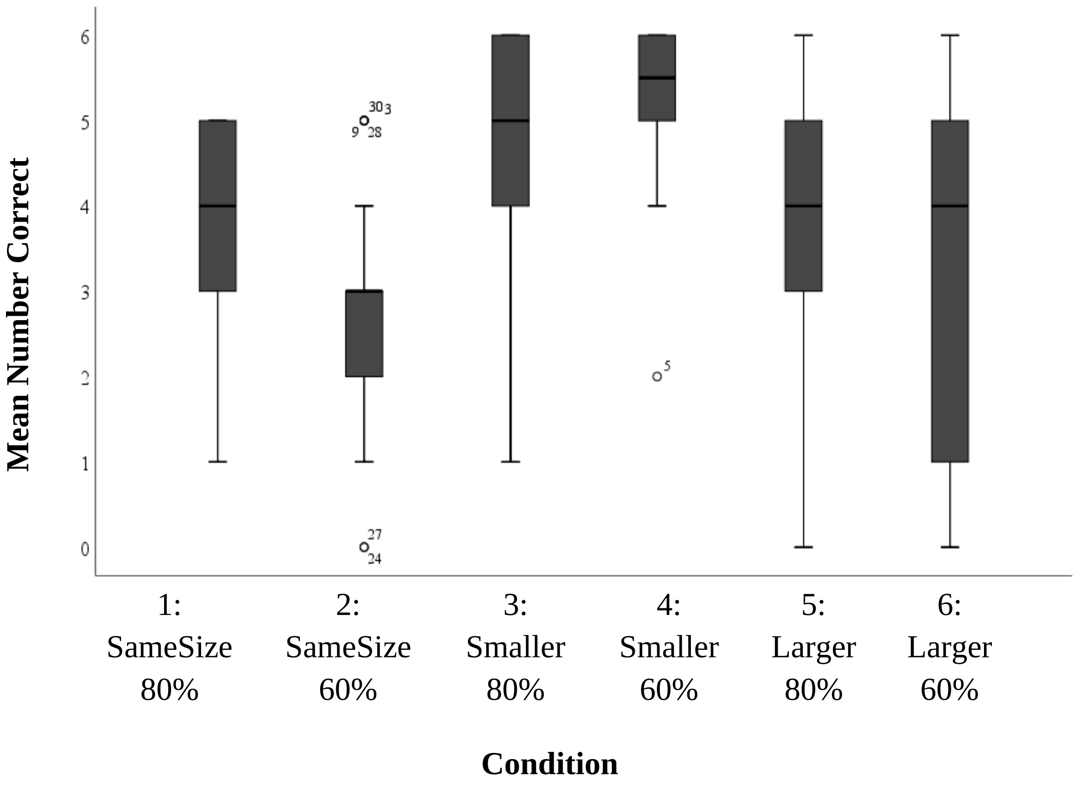


Figure 5-2. Box plot highlighting mean number of correct results during 6 conditions used to identify outlying data points.

As outliers in the data were identified (*Figure 5-2*), a Friedman ANOVA for non-parametric data was determined to satisfy the requirements of the current data (Field, 2014). Although a repeated measures ANOVA would potentially be robust to violations of assumptions that the current data set exhibits, the Friedman ANOVA with Bonferroni correction was deemed to provide a higher level of scrutiny of this investigation, thus aiding reproducibility of any potential findings during future studies. Median values from 6 conditions were calculated for the purpose of conducting a Friedman ANOVA. See Table 5-2.

Table 5-2. *Table showing the median number of correct answers (of 6) from 6 conditions.*

	Condition					
	1 SameSize 80%	2 SameSize 60%	3 Smaller 80%	4 Smaller 60%	5 Larger 80%	6 Larger 60%
Median Correct Responses	4.00	3.00	5.00	5.50	4.00	4.00

The Friedman ANOVA concluded that the number of correct answers given was statistically significant between conditions X^2 (2) = 68.824, *p* < .001. As a statistically significant difference was identified, further investigation was carried out by conducting post-hoc tests. A pairwise comparison with Bonferroni correction was used for this purpose. Considering these results first by comparing differences in shape pair size combinations with the same intensity, the number of correct answers during condition 2 (SameSize60%) (*Mdn* = 3.00) was significantly different to condition 4 (Smaller60%) (*Mdn* = 5.50) *p* < .001. Condition 4 (Smaller60%) (*Mdn* = 5.50) was also significantly different to condition 6 (Larger 60%) (*Mdn* = 4.00). Several other comparisons were significantly different but are of less pertinence. See Table 5-3 for all significant comparisons between conditions.

Table 5-3. *Matrix showing all significant comparisons between conditions from the Friedman ANOVA. Significant results were subject to Bonferroni correction and are signified with a '*' and relevant significance of accuracy between conditions.*

	SameSize 80% (1)	**SameSize 60% (2)**	**Smaller 80% (3)**	**Smaller 60% (4)**	**Larger 80% (5)**	**Larger 60% (6)**
SameSize 80% (1)				* $p < .001$		
SameSize 60% (2)			* $p < .001$	* $p < .001$	* $p = .045$	
Smaller 80% (3)						
Smaller 60% (4)						
Larger 80% (5)				* $p = .002$		
Larger 60% (6)			* $p = .006$	* $p < .001$		

5.4.1. Descriptive Statistics

This section will utilise descriptive statistics to explore the actual responses of participants during the shape size discrimination task. As the data analysed so far in this section focussed on correct/incorrect answers, it is pertinent to explore specific answers, particularly during conditions in which shapes were the same size but of differing intensities (1 and 2). Exploring answers during conditions 1 and 2 will aid understanding of how intensity differences affect perception of object size.

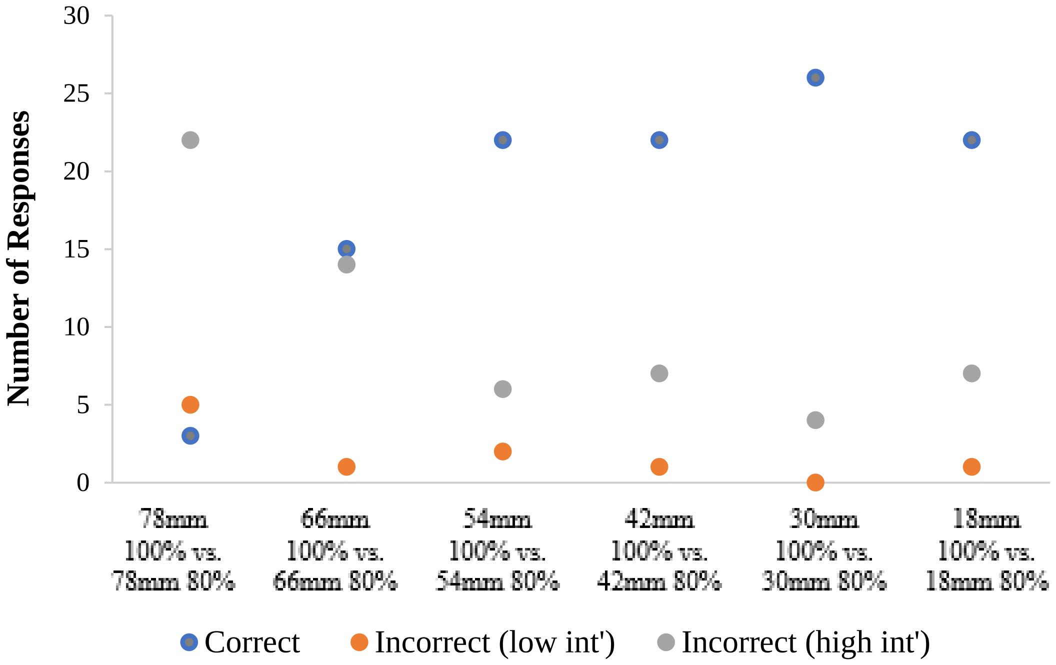


Figure 5-3. Scatter plot showing number of responses for Condition 1: shapes of the same size (100% vs. 80% intensity) in 3 categories; correct, incorrect (low intensity perceived as larger) and incorrect (high intensity perceived as larger) for 6 shape pairs during condition 1, in which both shapes were projected at the same size, but one was lower intensity (80%).

Figure 5-3 shows an apparent tendency for participants who answered incorrectly to confuse the shape that was projected at 100% intensity as being larger. This appears to be the case for all pairs during condition 1 and is demonstrated in the higher number of responses in the incorrect (high int’) category across all conditions.

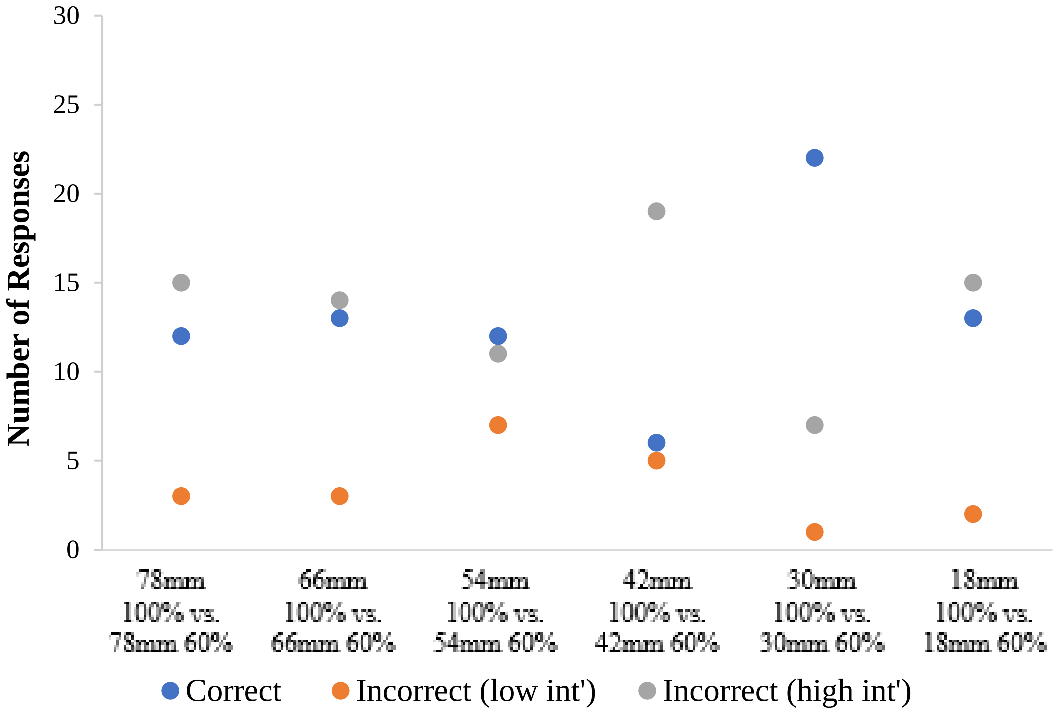


Figure 5-4. Scatter plot showing number of responses in Condition 2 in three categories for shapes presented at the same size (100% vs. 60% intensity); correct, incorrect (low intensity perceived as larger) and incorrect (high intensity perceived as larger) for 6 shape pairs during condition 1, in which both shapes were projected at the same size, but one was lower intensity (60%).

Figure 5-4 illustrates an exaggerated version of the trend seen in *Figure 5-3*, in which participants who answer incorrectly appear to do so because they deem the shape that was projected at 100% intensity as being larger than the one projected at 60%. This appears to be the case for all pairs during condition 2 and is demonstrated in the higher number of responses in the incorrect (high int') category. This is shown consistently and to a higher degree throughout all 6 shape pairs during condition 2 when compared to condition 1 and *Figure 5-3*.

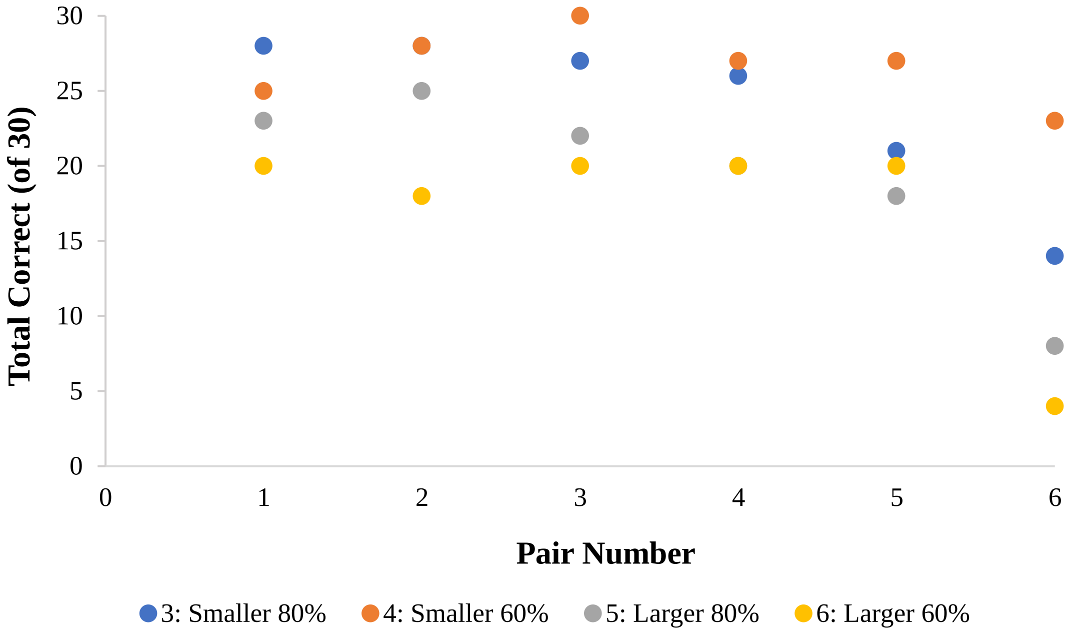


Figure 5-5. Scatter plot showing the total correct answers for all shape size pairs during the four conditions in which shape sizes differed (3-6). Pair numbers from 84mm vs. 18mm (left) to 54mm vs. 48mm (right) size difference.

Figure 5-5 shows a relatively linear number of correct answers during the first 5 shape pairs with a sharp decline in accuracy for the final shape pair. This is apparent in conditions 3, 5 and 6 but less so in condition 4, which maintains a relatively even number of correct responses throughout. The sharp decline in correct answers during the final shape pair suggests the limit in accurate determination of shape size difference was at this stage when the stimuli were 54mm vs. 48mm in size.

5.5. Discussion (Study 3)

The current investigation was conducted in order to establish whether UsHF intensity has an effect on user perception of object size. During an experiment in which the task was to establish which shape in a series of pairs of circles projected into mid-air using UsHF was largest, it can be concluded that UsHF intensity, depending on the specific object/intensity combination has a significant effect on the ability to correctly discern differences in object size.

As mentioned in the results section, there are a number of significant comparisons, as seen in Table 5-3, however, there are two comparisons that are of particular importance to the current investigation. The results of interest are as such because they compare conditions which both use the same intensity levels, so are directly comparable.

Firstly, the significant difference in the number of correct answers between condition 2 and 4 (condition 4 yielded a higher number of correct answers). Condition 2 represents objects of the same size with one projected at 100% intensity and the other at 60%. Condition 4 represents the larger stimulus projected at 100% intensity and the smaller at 60%. This significant comparison is notable because condition 2 was expected to yield one of the lowest numbers of correct answers if intensity influenced perception of size and condition 4 was expected to yield one of the highest correct response rates if participants shape exploration was not confounded with the intensity difference. These findings suggest several things. Firstly, when observing the low number of correct answers during condition 2, differing intensity is apparently often mistaken for differences in object dimensions. Secondly, when considering the high median number of correct scores during condition 4, it could be suggested that when subjective experience of intensity is normalised between larger and smaller shapes (they are made to feel the same intensity), users can accurately discern differences in object size. Another explanation for the high accuracy witnessed in condition 4 could be as a result of UsHF users having a predisposition to assume larger objects should feel more intense. In other words, having the larger object at 100% and the smaller one at 60% may have amplified the perceived size differences between them. This hypothesis fits with the analysis of condition 2, as hypothetically, participants assumed higher intensity was the larger object, which would result in a correct response, whereas assuming the higher intensity object was larger, as seen often during condition 2, would be incorrect.

Practically speaking, the significant difference in results between condition 2 and 4 allow for some recommendations to be made. Most salient of such advice is that changes in object intensity can be used as a cue for changes in object size without changing the size of the object. This could be beneficial in circumstances wherein a large shape projection is necessary, but the array is too small. Furthermore, if realistic and accurate rendition of object dimensions is necessary, intensity should be normalised to accommodate variation in subjective interpretations of object intensity. Although further work is required, these results suggest smaller shapes would be best rendered at 60% intensity, with larger objects remaining at 100%.

The second notable result illustrated in Table 5-3, is the significant difference between conditions 4 and 6. The stimuli within condition 6 were projected using different size objects, with the larger shape projected at 60% intensity and the smaller at 100%. This result is interesting as it gives credence to the low number of correct answers seen in conditions 1 and 2, illustrated in *Figure 5-4* and *5-5*, wherein individuals who answer incorrectly tend to select the shape of higher intensity as being larger. This also grants further confidence to the argument presented earlier, that the behaviour resulting in high accuracy during condition 4, could plausibly be attributed an unconscious assumption that large UsHF shapes should feel more intense. *Figure 5-3* shows that condition 6 yielded the most variation in the number of correct answers given. This is interesting because it suggests that in some circumstances, the extra cue of intensity representing certain object sizes could be confusing to some individuals and beneficial to others. It is not clear whether there is a measurable determinant of this effect.

Turning attention to the descriptive statistics segment of the results section. *Figures 5-4* and 5-*5* illustrate some interesting findings. When attempting to understand the response tendencies of participants when they answered incorrectly, both figures show that individuals more regularly selected the shape of higher intensity as the object they perceived as being largest. This is a particularly salient finding because it suggests that there is an element of predictability to how users will respond to stimuli of varied intensities. During studies 1 and 2 (Chapter 4) which used the same types of stimuli, it appeared possible for participants to judge size more accurately with the extra cue of intensity differences that arose as UsHF objects in their current state make larger objects feel less intense than smaller objects. In this instance with different and randomised intensity/size combinations, this study suggests some participants naturally gravitate towards assuming more intense shapes are larger when they are in fact the same size. This is particularly apparent when the stimuli differ in intensity by ~40% as shown in *Figure 5-5*. This could explain why conditions 3 and 4 witnessed some of the highest number of correct answers, because those conditions utilised larger shapes delivered at a higher intensity, thus satisfying potential preconceptions from the participants.

Finally, *Figure 5-6* demonstrates the limit of accurate perception of size difference during conditions 3, 5 and 6 was met during the shape pair 6, during which the shape sizes were 54mm and 48mm, which are very similar. Interestingly, the sharp decline in number of correct responses was not witnessed during condition 3. It is unclear why this is.

It can be concluded that differences in UsHF intensity can indeed affect user's perception of mid-air object sizes. The most relevant demonstration of this can be seen during condition 1 and 2 as there was no difference in object size, only object intensity. Despite being able to stipulate the existence of this effect, further queries have been realised during the investigation. Namely, it is unclear why condition 1 and 2, which demonstrate the ability for intensity alone to affect perception of size, differed so drastically to condition 3 and 4, which could be interpreted as demonstrating accurate shape size discrimination abilities when subjective intensity is normalised. Future investigations would likely benefit from exploration of psychophysical determinants of the confounding effects UsHF intensity can have on perceived shape size.

5.6. Conclusion (Study 3)

It can be concluded that during the size discrimination task mentioned during Section 5.3, that ultrasound intensity had a significant effect on how participants perceived UsHF object size differences. The most relevant finding that supports this conjecture is that when pairs of objects were the same size but presented at different intensities, that a significant proportion of participants perceived a size difference, particularly when the intensity of same size objects differed by 40%. It was also established with a degree of certainty that intensity could be normalised for different size objects, in this instance when smaller objects were projected at 60% with the larger at 100% (*Figure 5-6*). Future research should aim to understand how to normalise subjective intensity of UsHF objects to avoid the use of confusing stimuli.

5.7. Chapter Summary

This chapter was built upon the findings from the previous chapter, which were used to understand how UsHF intensity affects perception of object size. This work was a precursor to the later research conducted in Study 4 (Chapter 6) and gave insight into how intensity could be normalised for smaller/larger UsHF objects. It also provided valuable data on how much intensity can affect perception of object size when it was manipulated but object size remained the same. It also found that when users were answering incorrectly that they tended to assume the object of higher intensity was larger. Furthermore, this chapter also gave some clarity on what the limitations in size discrimination were whilst using UsHF.

Chapter 6: Multimodal Interaction with Ultrasound Haptic Feedback

6.1. Chapter Overview

This chapter explores the multimodal element of UsHF by incorporating visual feedback to various mid-air object discrimination tasks in order to satisfy objective 4 (Section 1.4.2). This chapter further incorporates exploration of object size and intensity discrimination as well as exploring effectiveness in aforementioned tasks when using physical analogues of mid-air objects, thus satisfying objective 5 (Section 1.4.2).

6.2. **Study 4 –** Multimodal Detection of Shape Size Using Ultrasound Haptic and Visual Feedback

6.2.1. Introduction and Rationale

Most past and existing VR interfaces only stimulate the visual, and sometimes the auditory senses. As demonstrated in the literature (Chapter 2), this can often be detrimental to user interaction with virtual objects, as in the absence of tactile feedback users are unable to feel the virtual world around them, and thus, have to compensate for this deficit, usually by relying on visual feedback. Multimodality comprising of both visual and haptic feedback seeks to alleviate this issue by offering users the ability to feel virtual stimuli, and thus, be more effective and accurate in a virtual world, whilst improving realism and immersion in the environment. However, implementations of multimodality are not as simple as it may seem, due in part to perceptual differences in how users process and prioritise different sensory information. Based on the literature, there are numerous examples of sensory dominance and prioritisation that can occur when presented with several sensory mediums, for example, visual dominance over haptic (e.g., Gibson J. , 1933), and haptic dominance over visual (e.g., Hanson, Whitaker, & Heron, 2009), thus, raising questions pertaining to understanding of how the introduction of visual stimuli affects the perception of UsHF stimuli and vice versa. At present, it is unclear whether these findings translate to implementations of UsHF.

The study reported in this section was created in order to explore findings from previous research in greater detail, and to explore anecdotal evidence of issues highlighted in previous studies conducted for this thesis. For example, Studies 1 (Section 4.2) and 2 (Section 4.3) revealed that individuals could perceive differences in object intensity, usually this manifested in a belief that larger objects were of a lower intensity. Although this may have technically been well-founded, the objects were in fact presented at the same intensity. This motivated the creation of stimuli that were of the same size but varied intensity. Study 3 (Chapter 5) later revealed the tendency for participants to perceive differences in object intensity as difference in size. Furthermore, this investigation introduces the multimodal (visuo-haptic) element to this PhD and seeks to understand how UsHF affects the size discrimination process when presented with visual information. This will demonstrate whether UsHF benefits size perception of virtual objects, as well as aiding understanding on the conscious and unconscious prioritisation/dominance of visual (virtual) and UsHF stimuli. In order to do this, this investigation utilises pairs of stimuli with size differences presented with different combinations of object size and intensity in conditions with and without multimodal feedback. Furthermore, due to the nature of the stimuli set included, this research also seeks to understand in a rudimentary fashion, whether object intensity can be normalised to yield accurate UsHF object size recognition.

It was hypothesised that the presence of UsHF would improve visual-only and haptic-only object size discrimination. Comparisons that were expected to yield interesting results due to findings from previous studies were haptic only vs. visual only, as this would establish baseline accuracy in the absence of the multimodal element. Visual only/haptic only vs. haptic and visual congruent would explore the effect of multimodal interaction. As aforementioned, haptic and visual congruent vs. haptic and visual incongruent could reveal the presence of sensory dominance or prioritisation. The introduction of multimodality to the research conducted for this PhD is key in satisfying one of the main aims this work set out to address, as well as being key to the natural progression of research into applied UsHF.

6.2.2. Method (Study 4)

This section will explore the experimental method employed during Study 4

Participants

During this investigation, 11 males and 12 females took part on a voluntary basis. As demographics were no longer of interest, these data were not collected. Of these, 10 participants had prior experience using UsHF, whereas 13 did not. Participants were required to verify their suitability for the study by confirming they had no impairments that prevented normal use of their hands or their ability to detect tactile stimuli. Participants were paid a £10 Amazon voucher for taking part.

Equipment

The equipment used to create mid-air stimuli can be seen in Section 3.5, general equipment. Additionally, a 22" monitor placed in front of the array was used to display visual stimuli (see *Figure 6.2-1*).

Figure 6.2-1. Two images of the current setup including the ultrasound array and monitor that was used to display visual stimuli during multimodal conditions.

The response form used allowed participants to select which object they thought was largest (A or B). The form also allowed them to select "same size" if they thought both A and B were the same size. See Appendix D and F for a summary of the supplementary documents that were used during this study.

Stimuli

There were 10 sets of stimuli used in total, 2 of which varied in intensity only (1-2) and 8 in both size and intensity combinations (3-10) (see Table 6.2-1).

Table 6.2-1. *Table outlining the various stimuli sizes/intensities, the combinations and order in which they were presented to participants.*

Stimuli Set	Object Pair Combinations		Example
1 - SameSize80%	87mm vs. 87mm 72mm vs. 72mm 57mm Vs 57mm	42mm Vs 42mm 27mm Vs 27mm	**42mm (100%) vs. 42mm (80%)**
2 - SameSize60%	72mm vs. 72mm 27mm Vs 27mm 57mm Vs 57mm	87mm vs. 87mm 42mm Vs 42mm	**57mm (100%) vs. 57mm (60%)**
3 - Smaller80% (12mm)	75mm vs. 87mm 60mm Vs 72mm 45mm vs. 57mm	30mm Vs 42mm 15mm vs. 27mm	**87mm (100%) vs. 75mm (80%)**
4 - Smaller60% (12mm)	15mm vs. 27mm 60mm Vs 72mm 75mm vs. 87mm	45mm vs. 57mm 30mm Vs 42mm	**60mm (100%) vs. 72mm (60%)**
5 - Larger80% (12mm)	30mm Vs 42mm 75mm vs. 87mm 15mm vs. 27mm	45mm vs. 57mm 60mm Vs 72mm	**15mm (100%) vs. 27mm (80%)**
6 - Larger60% (12mm)	30mm Vs 42mm 15mm vs. 27mm 60mm Vs 72mm	75mm vs. 87mm 45mm vs. 57mm	**45mm (100%) vs. 57mm (60%)**
7 - Smaller80% (6mm)	81mm vs. 87mm 72mm vs. 66mm 51mm vs. 57mm	42mm vs. 36mm 27mm vs. 21mm	**87mm (100%) vs. 81mm (80%)**
8 - Smaller60% (6mm)	51mm vs. 57mm 81mm vs. 87mm 27mm vs. 21mm	72mm vs. 66mm 42mm vs. 36mm	**66mm (100%) vs. 72mm (60%)**
9 - Larger80% (6mm)	42mm vs. 36mm 81mm vs. 87mm 72mm vs. 66mm	51mm vs. 57mm 27mm vs. 21mm	**21mm (100%) vs. 27mm (80%)**
10 - Larger60% (6mm)	42mm vs. 36mm 51mm vs. 57mm 72mm vs. 66mm	27mm vs. 21mm 81mm vs. 87mm	**51mm (100%) vs. 57mm (60%)**

These stimuli sets were created using knowledge gained from previous studies in order to determine the pair combinations best suited for the current experiment. Looking at Table 6.2-1, each set can be seen. The terminology (e.g., SameSize) stipulates that both shape A and B were the same size, and the "80%" signifies that of those objects, one was projected at 80% intensity, with the other remaining at 100%. This was the case for sets 1-2. When the stimuli were not the same size, the set is referred to, as an example, "Smaller80%". This classification means of the two objects in a pair, the one that was smaller was projected at 80% intensity, with the other remaining at 100%. Conversely, "Larger80%" signifies that the larger object was presented at 80% intensity, and the smaller object at 100%. Stimuli sets 3-10 were further manipulated by altering the size differences between each pair, meaning each set was presented with both 12mm and 6mm difference in size. For example. In total there were 10 sets of stimuli, each containing 5 pairs of objects, for a total of 50 pairs during each condition (haptic only; vision only; haptic and visual congruent; haptic and visual incongruent – Table 6.2-2). As the object intensity could not be manipulated during the visual only condition (2), the same stimuli set was used, without the variation in intensity

Study Design

Participants took part on a within-subjects basis, as such, participants took part in all 4 conditions. See Table 6.2-2 for a summary of these conditions.

Table 6.2-2. *Table summarising 4 conditions, including which sensory mediums were used, with descriptions of participant activities during each condition.*

Condition	Description
1 – Haptic Only	Participants discriminating size differences using only UsHF
2 – Visual Only	Participants discriminating size differences using only visual representations of virtual stimuli on screen
3 – Haptic & Visual Congruent	Participants discriminating size differences using both UsHF and matching visual representations of UsHF objects displayed on screen
4 – Haptic & Visual Incongruent	Participants discriminating size differences using both UsHF and visual objects displayed on screen. Visual objects were switched so they did not match UsHF objects (e.g., the largest object on screen was shape A, but the largest using UsHF was B)

The task was to discern which object in a pair was largest or whether they were the same size using a series of feedback mediums during each condition. The order in which participants took part in each condition was counterbalanced to minimise the likelihood of practice effects and the impact of learnt behaviour. Condition 1 was included to illustrate size discrimination accuracy using only UsHF so it could be compared to multimodal conditions. Condition 2 was designed to give insight into ability on the same task but using vision only to determine object size. Both condition 1 and 2 could be considered control conditions before implementation of conditions requiring both haptic and visual perception. Condition 3 was used to understand the impact of UsHF on a multimodal object size perception task, particularly when compared to condition 2, which is analogous to virtual environments with no tactile feedback. Condition 4 was designed to understand whether users prioritised either haptic or visual information. This was achieved by displaying different sized objects through the visual and haptic interfaces. Results were marked based on which object was largest on the UsHF array. This meant for example, if shape B was largest on screen and participants were selecting object B as the largest, that users could be consciously or subconsciously prioritising visual feedback or that they may lack trust in UsHF. Users were instructed to pay equal attention to both haptic and visual information during condition 3 and 4. Participants were given breaks when required.

Procedure

Participants were given a brief and consent form to sign (see Appendix D) before attending their allocated slot. Participants took part in a short training period (see Section 3.2.1.1). Participants were asked to put on the headphones and confirm whether they could hear the white noise being played. White noise was played at a volume which masked the sound of the ultrasound array but not the researcher's voice. Participants took part in the first condition allocated to them, for example, participant 1 would start on condition 1 and end on 4, participant 2 would begin on condition 2 and end on condition 1, and so on.

Participants received verbal prompts to notify them which shape (number) they were interacting with. Participants were presented with one object of the pair at a time, they could feel each shape for up to 30 seconds. Participants explored the first shape then moved their hand away from the array whilst the second shape was projected, they then felt the second shape and made their judgement on which was largest by placing a tick in the corresponding box on the answer sheet. If they believed the shapes to be of the same dimensions, they placed a tick in the "No Difference" box on the answer sheet. This was repeated for all four conditions.

Participants responded to each object pair via a Microsoft form. After completing all 4 conditions, participants were given a £10 Amazon voucher for taking part.

6.2.3. Results (Study 4)

In order to determine the appropriate analysis, the data were first inspected and were subject to analysis for outliers using a boxplot. See *Figure 6.2-2*.

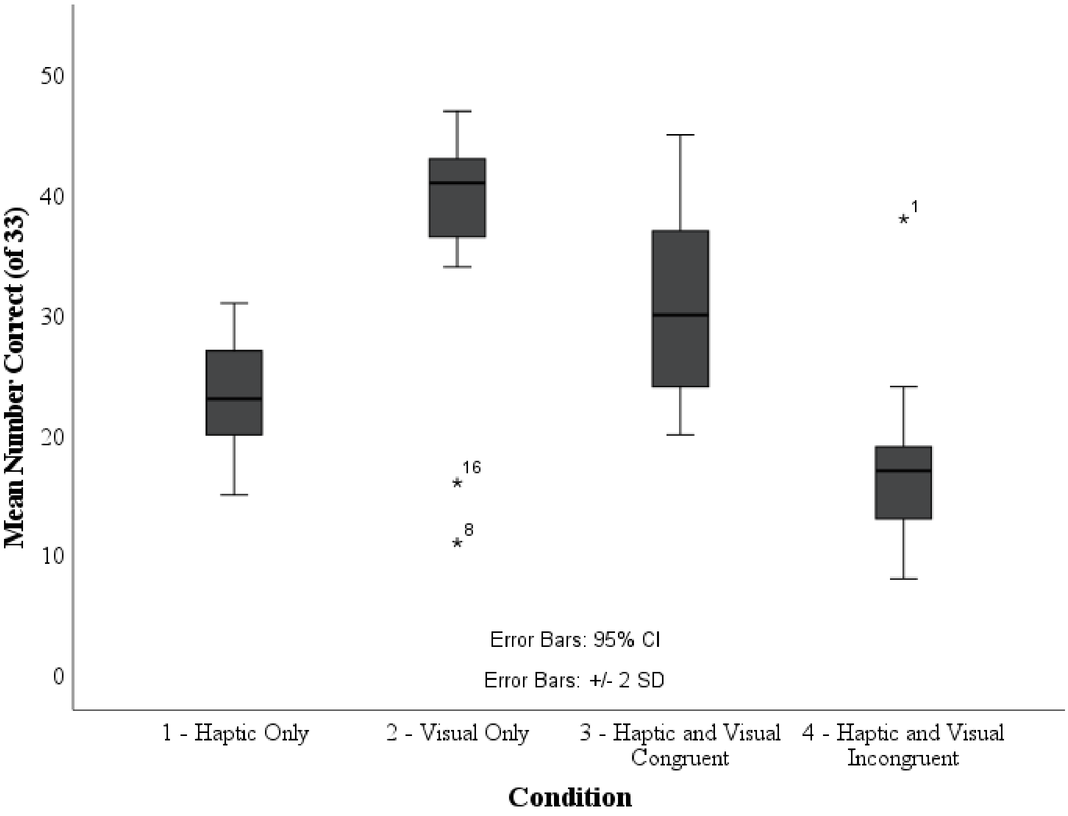


Figure 6.2-2. Box plot showing mean number of correct answers during 4 conditions. Box plot highlights the presence out outlying data points.

Figure 6.2-2 highlights the presence of outlying data points. The reason for these abnormal points is unclear. Despite there being only three outliers, the assumption of normal data for the purpose of a repeated measures ANOVA was violated, thus a Friedman ANOVA was determined to be more suitable to analyse these data. After running a Friedman ANOVA, it was discovered that accuracy during the size discrimination task was significantly different during 4 conditions $\chi2(3) = 42.563$, $p < .001$. As there was a statistically significant difference between conditions, pairwise comparisons with Bonferroni correction were conducted in order to determine where those differences occurred. See Table 6.2-3 for a summary.

Table 6.2-3. *Table exploring pairwise comparisons conducted for 4 conditions. Significant differences are highlighted (**).*

Condition Comparison	**Test Statistic**	**Std. Error**	**Std. Test Statistic**	**Significance**	**Adjust' Sig**
Hap & Vis Incongruent (4) vs. Haptic Only (1)	.826	.381	2.170	.030	.180
Hap & Vis Incongruent (4) vs. Hap & Vis Congruent (3)	1.652	.381	4.340	<.001**	.000**
Hap & Vis Incongruent (4) vs. Vis Only (2)	2.304	.381	6.053	<.001**	.000**
Haptic Only (1) vs. Hap & Vis Congruent (3)	-.826	.381	-2.170	.030	.180
Haptic Only (1) vs. Visual Only (2)	-1.478	.381	-3.883	<.001**	.001**
Hap & Vis Congruent (3) vs. Visual Only (2)	.652	.381	1.713	.087	.520

Table 6.2-3 reveals three statistically significant differences between conditions. These include haptic only (*Mdn* = 23) vs. visual only (*Mdn* = 41) (*p* = .001), haptic and visual incongruent (*Mdn* = 17) vs. visual only (*Mdn* = 41) (*p* < .001) and haptic and visual incongruent (*Mdn* = 17) vs. haptic and visual congruent (*Mdn* = 30) (*p* < .001). Median scores can be seen below in Table 6.2-4.

Table 6.2-4. *Median number of correct answers (of 50) during each condition.*

Haptic Only (1)	**Visual Only (2)**	**Hap & Vis Congruent (3)**	**Hap & Vis Incongruent (4)**
23	41	30	17

Descriptive statistics will be used to explore in more detail where differences in accuracy dependent on stimuli type lie.

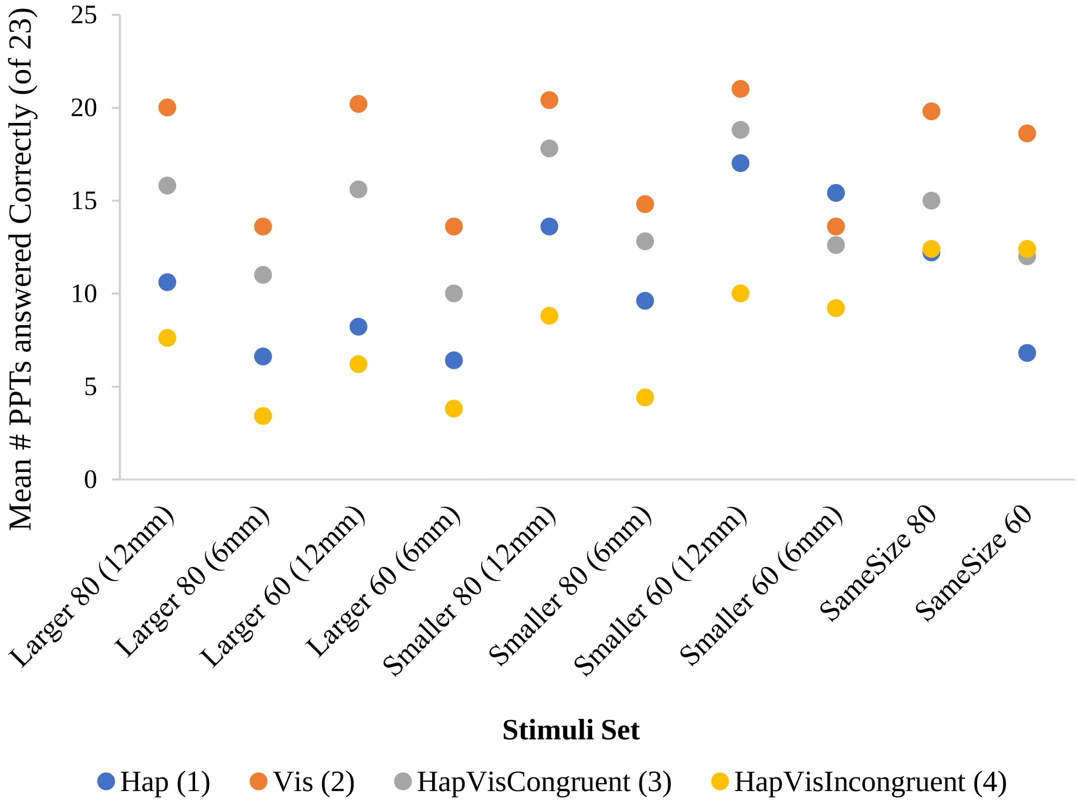


Figure 6.2-3. Scatter plot depicting mean number of correct answers for individual stimulus types during 4 conditions.

Figure 6.2-3 highlights some interesting patterns in mean accuracy whilst including both the stimuli type and the condition. It appears that accuracy for each stimuli set is relatively consistent across all 4 conditions, although haptic only performs uncharacteristically well for smaller 60 (.2), then worse for both same size conditions. It can be seen that conditions 3 and 4 yield roughly the same accuracy when participants were presented with objects of the same size. This was expected as it was naturally impossible to alter the order of objects as was implemented with stimuli of differing sizes. Intensity via UsHF was still manipulated though.

6.2.4. Discussion (Study 4)

The current study sought to establish whether UsHF could improve accuracy during multimodal (haptic and visual) size discrimination task. It was hypothesised that the addition of UsHF would improve visual-only size discrimination accuracy. The results demonstrate that the presence of UsHF did not improve perception of virtual objects, in fact, accuracy was highest during the condition in which participants were only given visual feedback, though was not statistically significant when compared to haptic and visual congruent (condition 3). See *Figure 6.2-2*.

In order to unpack these results, it is first salient to explore the differences seen between conditions. For the sake of discussion, comparisons that were previously expected to yield results of interest due to findings from previous studies were haptic only vs. visual only, as this would establish baseline accuracy in the absence of the multimodal element. Also, visual only/haptic only vs. haptic and visual congruent would explore the effect of multimodal interaction. As aforementioned, also, haptic and visual congruent vs. haptic and visual incongruent, could reveal the presence of sensory dominance/overload. There were three statistically significant differences, these were between haptic only vs. visual only, haptic and visual incongruent vs. visual only, and haptic and visual incongruent vs. haptic and visual congruent (see Table 6.2-3). This discussion will now discuss the implications of each comparison in isolation.

Firstly, the comparison between visual only (1) and haptic only (2). As the results demonstrate, visual only size discrimination was significantly better than haptic only (UsHF) size discrimination. This finding is particularly salient because it demonstrates that accurate perception of virtual object size is better via visual feedback than with UsHF. At this stage it is unclear whether this discrepancy is as a result of inadequate tactile feedback from ultrasound haptics, or whether this would occur with physical objects as well.

Secondly, the comparison between visual only (2) and haptic and visual incongruent (4). This condition comparison represents both the highest and lowest median accuracy respectively across all four conditions, with condition 4 scoring a median of 17, and condition 2 scoring 41. This is a pertinent finding because it highlights the extent to which participants favoured vision over tactile feedback during this task. Visual dominance not only manifests during the condition in which only visual feedback was given, but also during the condition in which participants were given contradictory haptic and visual information (4), wherein they more regularly elected to choose the largest visual object rather than the largest haptic object. The prevalence of low accuracy during the incongruent condition could be as a result of several effects. Firstly, it is possible that participants are naturally visually biased when it comes to size discrimination tasks, which is partially corroborated by the literature in which vision dominates tactile information during certain tasks (e.g., Gibson, 1933), although it is unclear whether this is a conscious or unconscious bias. Considering participants were instructed to pay attention to both haptic and visual information, the current evidence would suggest an unconscious visual bias. It is also conceivable that participants did not trust UsHF, which is supported, at least in part, by the relatively low accuracy seen during condition 1 and 4, with participants favouring visual feedback in the latter condition, though this remains speculative and cannot be confirmed given the current data. It is also possible that although trust in UsHF may have been present, participants simply could not be accurate on the task when relying on UsHF, or at the very least, considering the feedback it provided.

Finally, the comparison between haptic and visual congruent (3) vs. haptic and visual incongruent. This is possibly the most interesting result, as the conditions are directly comparable on the basis that they were both multimodal and participants received the same types of information. This comparison further supports the theory that participants demonstrate bias towards visual perception of size when also using UsHF. Again, whether this bias is conscious, or unconscious remains unclear.

Interestingly, there was no significant difference between visual only (2) and the condition utilising both haptic and visual (congruent) feedback (3). Whilst this is not necessarily a finding in support of the use of UsHF, it also shows that UsHF was not significantly detrimental to determining virtual object size differences. Though the cause is unknown based on current findings, it is possible that whilst the presence of UsHF does not improve task accuracy compared to efforts during the visual only condition, it may improve the individual sense of immersion and other subjective experience measures, as indicated in Chapter 6. Thus, the justification for the use of UsHF in multimodal scenarios could migrate from the realm of task accuracy improvement to the domain of experience-based improvements as aforementioned. This would be an interesting finding as it could still influence people's desire to use the technology, though there is no way to verify this based on current findings.

6.2.5. Conclusion (Study 4)

This study was conducted in order to measure object size discrimination accuracy in both unimodal (haptic only and visual only) and multimodal (visuo-haptic) conditions. The results demonstrate firstly that though the congruent visuo-haptic condition did not yield higher accuracy than visual only, it was also not significantly worse, suggesting that UsHF could be applied to multimodal tasks without having a negative impact on perception of virtual objects size. Whilst on the surface this finding might be discouraging, there could still be other benefits to multimodal UsHF, such as subjective benefits to realism, enjoyment and presence that have a positive impact on the virtual experience. A further observation was that with UsHF alone, users could not as accurately discern virtual object size of the current stimuli when compared to visual alone. This may have implications for gesture-based human-machine interfaces that do not provide visual feedback to the user, particularly if those interfaces require a high level of haptic differentiation, e.g., projecting several 'buttons' of different sizes at a time. However, it is worth mentioning that the stimuli used during this investigation were an experimental set and may not represent real-world accuracy in virtual object size discrimination. Furthermore, the object size differences used were already on, or close to the limit of discernible size differences that was established during Study 1 (Section 4.2) and Study 3 (Chapter 5). Finally, the results indicate that there was a prioritisation of visual stimuli, evidenced by the fact that participants more regularly elected to select the item of largest size to be the one shown on screen during condition 4. It remains unclear whether this is conscious, or unconscious and what the reason for this effect is, however, it is a salient finding that could have an effect on future research and implementations of multimodal UsHF.

6.2.6. Limitations (Study 4)

Naturally, the 2D multimodal environment implemented during this study is not necessarily analogous of a 3D VR environment that UsHF is sought to be implemented within engineering applications, thus concrete conclusions cannot be drawn based on the current findings. However, the method utilised during this study serves as a proof of concept and certainly contributes to theory that can be learnt from and applied to future, more immersive studies.

6.3. **Study 5 –** Perception of Ultrasound Haptic Feedback and Physical Objects

Study 5 comprised of three experiments, experiment 1 sought to measure UsHF mid-air objects in order to create physical analogues, experiment 2 was conducted in order to establish a paradigm for normalisation of subjective intensity of UsHF objects, and experiment 3 aimed to apply the data from the aforementioned experiments by conducting a multimodal size discrimination task and comparing results to size discrimination of physical objects. Each experiment will be evaluated in the following three sections (6.3.2 - 6.3.4).

6.3.1. Introduction and Rationale

This study is the final in the series of quantitative work for this PhD and was the culmination of all knowledge gained from the literature and previous studies. Further to the previous investigation (Section 6.2), this study sought to investigate several elements. Firstly, in order to conduct the latter part of this study, it is necessary to be able to create physical analogues of UsHF objects. This will be achieved first by projecting them into oil in order to view them visually then measuring UsHF object sizes. Secondly, it is essential that this PhD addresses the normalisation of UsHF intensity for all object sizes available in order to ensure that users feel mid-air objects consistently across the size spectrum. Finally, the aforementioned actions will be implemented in a size discrimination study which aims to establish if normalised stimuli are employed and participants are given multimodal feedback, whether a visuo-UsHF interface can illicit the same size discrimination accuracy when compared to physical objects created based upon the same UsHF stimuli.

In understanding how people perceive multimodal objects, it is possible to begin building a picture of what interaction with multimodal UsHF might look like in applied settings. If for example, there are issues with how individuals perceive object size compared to physical objects, it may make users less willing to shift from physical engineering design stages to UsHF with VR.

6.3.2. UsHF Object Measurement (Study 5 – Experiment 1)

In order to create the physical objects required for Experiment 2 of this study, it was imperative to gauge accurate measurements of existing UsHF objects to be used during part 3 of the experiment. This section will address the method and results from the object measurement experiment as part of study 5.

6.3.2.1. Method (UsHF Object Measurement)

As the Ultraleap software (Sensation Editor) refers to object size differences as a measure of "x", e.g., 1.5x, an investigation was carried out to establish the real-world size differences between objects. This was achieved by projecting mid-air objects onto the surface of illuminated cooking oil, a technique used by Long, Seah, Carter and Subramanian (2014). The objects were then measured against a physical scale present alongside the projected objects. See *Figure 6.3-1* which demonstrates this technique. Torus objects from 0.4x up to 2.5x were measured using this method, testing a total of 22 rings produced in the Ultraleap Sensation Editor.

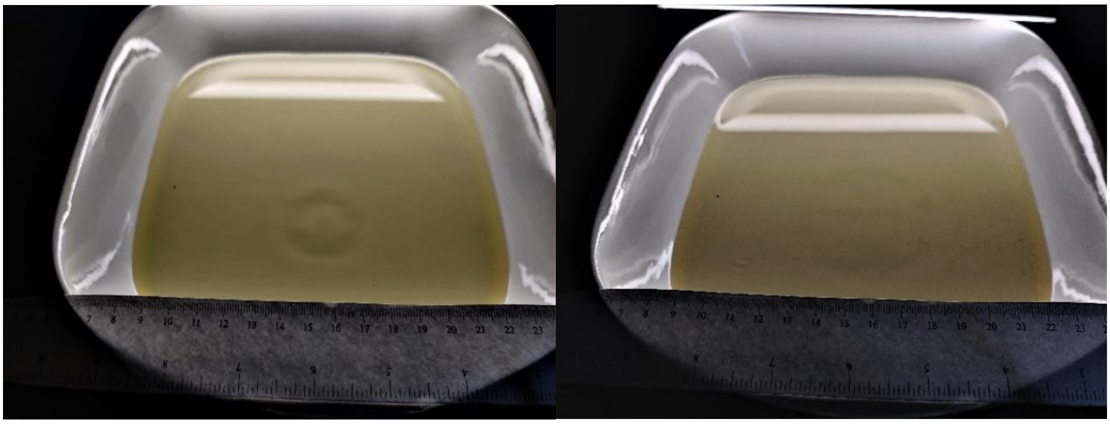


Figure 6.3-1. UsHF objects projected into illuminated oil with physical scale to aid measurements of the otherwise invisible objects.

After each shape increment was projected into the oil, it was photographed. The objects were then measured by adding digital lines to the outer diameter of each object which then aligned with the physical scale, allowing measurements to be taken.

6.3.2.2. Results (UsHF Object Measurement)

It was found with relative reliability, that each increment of 15mm (the smallest increment allowed in the Ultraleap Sensation Editor), corresponded to approximately 3mm in real-world size difference, with 0.1x representing a 15mm OD, thus a 0.2x object has an OD of 18mm. After measurements of the UsHF rings objects were recorded, the information was used to create analogous 3D printed versions. More information on these will be provided in the ‘Stimuli’ subsection in the primary section of this investigation (6.3.2.3).

6.3.3. UsHF Object Intensity Normalisation (Study 5 – Experiment 2)

This section will address the method and results from the object intensity normalisation experiment as part of study 6.

6.3.3.1. Method (UsHF Object Intensity Normalisation)

This section will outline the methods used to normalise perceived differences in UsHF object intensity when the object size changes. Normalisation refers to evidence that suggests subjective intensity feels lower when objects are larger, and higher when smaller. In order to make sure users are provided with stimuli that ‘feel’ the same, normalisation is required.

Participants

5 participants recruited internally from the University of Nottingham took part in the object normalisation segment of this experiment on a voluntary basis. All participants were screened for suitability before taking part and were required to have unaffected tactile perception and normal use of their hands to be eligible. As there were previously no individual differences attributed to object size/intensity detection, a large sample was deemed not necessary to achieve the goal of establishing rules for normalisation of subjective UsHF intensity. Participants volunteered and were not paid for taking part.

Equipment

The equipment used to create mid-air stimuli can be seen in Section 3.3, general equipment. For a summary of the forms used during this study, see Appendix E and F.

Stimuli

The characteristics of the stimuli used for this section of the study were selected based on findings from previous investigations. The stimuli were chosen both for the purposes of normalisation for the main experiment as this is the same stimuli set that will be used, but also because they will help create a general rule for wider normalisation of object intensity during other applications.

Table 6.3-1. *Table illustrates the stimuli used, how they were paired, the size difference and the number of times each stimuli set was used.*

Stimuli Sets/Pairs		**Size Difference**	**No# of Times Included**
87mm vs. 24mm 84mm vs. 27mm 81mm vs. 30mm 78mm vs. 33mm 75mm vs. 36mm 72mm vs. 39mm	69mm vs. 42mm 66mm vs. 45mm 63mm vs. 48mm 60mm vs. 51mm 57mm vs. 54mm	Gradual decrease in size difference starting with **63mm** ending with **3mm difference**	**1** (11 pairs total)
87mm vs. 75mm 72mm vs. 60mm	57mm vs. 45mm 42mm vs. 30mm	**12mm**	**2** (8 pairs total)
87mm vs. 81mm 78mm vs. 72mm 69mm vs. 63mm 60mm vs. 54mm	51mm vs. 45mm 42mm vs. 36mm 33mm vs. 27mm	**6mm**	**2** (14 pairs total)

Table 6.3-1 shows the stimuli used. The stimuli set with gradually decreasing size differences was chosen as it will help determine the exact point at which users stop being able to accurately discern size during the main experiment. These stimuli were used early during studies 1 and 2 and often found this limit to be approximately 6-12mm. This also enables the normalisation of intensity across the entire spectrum of perceptible objects. Stimuli with differences of 12mm and 6mm were chosen primarily for the main experiment, but also enabled the more accurate normalisation during this part of the investigation as combinations were repeated several times.

Study Design

This study had one condition in which the task was to portray the perceived intensity differences between the first and second object of each pair. This was repeated for a total of 33 randomised object pairs that can be seen in Table 6.3-1. The first object in a pair was always larger than the second, however the sizes of the first and second varied. The first object was always presented at 100% intensity, as was the second initially. Establishing a normalised intensity was achieved by gradually reducing the intensity of the second object until the participant reported the intensities to match. Intensity was reduced in 10% increments. After each intensity adjustment to the second object, the participant would feel the first object again, then the adjusted second object. Much like the method employed during the tactile threshold tests during study 2, once the participant reported a match in object intensity, the second object intensity was increased until it was reported not to match the first object. The result was then marked on a response form by the researcher.

Procedure

Participants were given a brief and consent form to sign (see Appendix E) before attending their allocated slot. Participants were asked to put on the headphones and confirm whether they could hear the white noise being played. White noise was played at a volume which masked the sound of the ultrasound array but not the researcher’s voice. Participants took part in a short training period (see Section 3.2.1.1). During the trial, the participant would feel the first shape, which was always the largest of the two. This is because subjective reports during previous studies suggested that the larger objects felt less intense than the smaller objects (Study 1 [Section 4.2] and Study 2

[Section 4.3]). After feeling the first object, participants would move their hand away from above the ultrasound array, they would feel the second and report to the researcher whether they thought they were the same intensity. If for example, they perceived both objects to be the same intensity, the second object intensity would be decreased until they perceived a difference, at which point it would be raised again until deemed matching. Once matching again, this was the intensity difference recorded. If the intensity of the second object was perceived as being higher than the first, the same method was employed. This was then repeated for the remaining pairs of objects.

6.3.3.2. Results (UsHF Object Intensity Normalisation

Table 6.3-2. *Shows intensity changes required to create normalised intensity levels for different sized objects.*

Object Size Difference	**Intensity Difference**
15mm	0%
0.18x – 27mm	10%
30mm – 69mm	20%
72mm – 75mm	30%

Table 6.3-2 illustrates the difference in intensity that should be applied to specific object size differences in order for them to be perceived as the same intensity. For example, Presenting the first object with a size of 42mm at 100% intensity would require the second object of 36mm in size to be presented using 90% intensity so the objects have the same subjective feeling. Notice this is particularly important as the object size difference increases.

6.3.4. Object Size Discrimination Task (Study 5 – Experiment 3)

This section will examine the method and results from the third and final experiment for study 6, in which participants took part in an object size discrimination task using both UsHF and physical objects.

6.3.4.1. Method (Object Size Discrimination Task)

This section will explore the methodology used for part 3 of study 6.

Participants

A total of 30 participants (17 male and 13 female) recruited internally from the University of Nottingham took part on a voluntary basis. Participants were screened for the same requirements as during the object intensity normalisation study (Section 6.3.3). 14 participants had used UsHF before, whereas 16 had not. Participants were paid a £10 Amazon voucher for taking part.

Equipment

The equipment used to create mid-air stimuli can be seen in Section 3.3, general equipment. In addition to the UsHF equipment, a 22” monitor was used to show participants visual representations of mid-air objects. An example of these will be provided in the following subsection. The physical objects were 3D printed; more information will be provided during the stimuli subsection.

A questionnaire was administered during this study. The questionnaire comprised of both short and long-answer questions which asked participants about subjects such as their work background, experience with UsHF and VR as well as their expectations of UsHF and experience during the study. The full questionnaire can be found in Appendix E

Stimuli

This section will cover both the ultrasound and physical stimuli used for the main portion of the experiment. The ultrasound stimuli can be found in Table 6.3-1 and were the same stimuli used during the object intensity normalisation study (Section 6.3.3). These stimuli were used as they offered both large variation in object size differences, but also variation that elicited lower accuracy when detecting size differences (24mm and 18mm difference).

Physical objects were 3D printed based on the findings during the object measurement study (Section 6.3.2) which asserted that the ultrasound object size increments equated to real world Outer Diameter (OD) differences of approximately 3mm (see *Figure 6.3-2*).

Figure 6.3-2. Example of 3D printed tori, printed to match the size increments of UsHF mid-air objects.

The physical objects were all the same torus thickness of 12mm to maintain a consistent grasping area. The only dimension manipulated on the physical objects was the OD. Naturally, the inner diameter (ID) changes as a biproduct of a varied OD and constant torus thickness, as is the case for the rings projected using UsHF. Table 6.3-3 will explore the dimensions of the stimuli used during this study.

Table 6.3-3. *UsHF object sizes, pair combinations and order of stimuli.*

UsHF (Condition 1) Object Order	**Physical (Condition 2) Object Order**
87mm vs. 24mm	60mm vs. 54mm
66mm vs. 45mm	87mm vs. 75mm
57mm vs. 54mm	87mm vs. 81mm
87mm vs. 75mm	72mm vs. 60mm
69mm vs. 42mm	84mm vs. 27mm
51mm vs. 45mm	69mm vs. 63mm
33mm vs. 27mm	42mm vs. 36mm
72mm vs. 60mm	63mm vs. 48mm
72mm vs. 39mm	57mm vs. 45mm
87mm vs. 81mm	42mm vs. 30mm
51mm vs. 45mm	42mm vs. 36mm
57mm vs. 45mm	33mm vs. 27mm
87mm vs. 81mm	87mm vs. 75mm
60mm vs. 54mm	60mm vs. 54mm
72mm vs. 60mm	72mm vs. 39mm
81mm vs. 30mm	42mm vs. 30mm
63mm vs. 48mm	87mm vs. 24mm
78mm vs. 72mm	72mm vs. 60mm
33mm vs. 27mm	51mm vs. 45mm
69mm vs. 63mm	57mm vs. 45mm
60mm vs. 51mm	69mm vs. 63mm
42mm vs. 36mm	66mm vs. 45mm
87mm vs. 75mm	33mm vs. 27mm
42mm vs. 30mm	78mm vs. 72mm
84mm vs. 27mm	78mm vs. 33mm
78mm vs. 72mm	69mm vs. 42mm
57mm vs. 45mm	51mm vs. 45mm
60mm vs. 54mm	87mm vs. 81mm
42mm vs. 30mm	75mm vs. 36mm
78mm vs. 33mm	57mm vs. 54mm
42mm vs. 36mm	60mm vs. 51mm
75mm vs. 36mm	81mm vs. 30mm
69mm vs. 63mm	78mm vs. 72mm

In total, there were 21 ultrasound and physical objects combined in the pairs seen in Table 6.3-1 for a total of 33 pairs of objects in each condition. As aforementioned, the mid-air objects were also presented to participants in 2D form on a monitor. *Figure 6.3-3* is an example of the virtual visual stimuli.

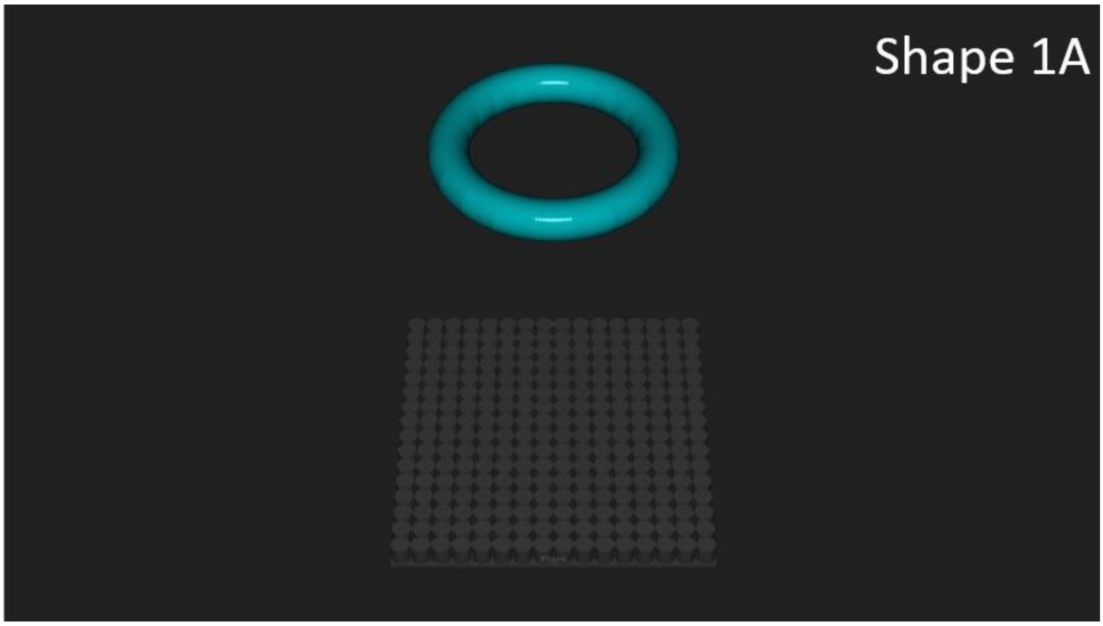


Figure 6.3-3. An example of the visual element shown to participants during the UsHF condition (1). Visual included a rendition of the ultrasound array to maximise immersion.

Study Design

This experiment utilised a within-subjects design in which the participant's task was to discern size differences between pairs of objects. The experiment consisted of 2 conditions, UsHF with visual element (Condition 1), and physical objects (Condition 2). Both conditions included the same 33 pairs of objects (torus) seen in Table 6.3-1, albeit in a different, randomised order. Both the pair order and the first/second shape order was different between conditions 1 and 2. Participants took part in both conditions in the same order (1 then 2). Prior to taking part in condition 1 and 2, participants took part in a training period (see Section 3.2.1.1). During condition 2, participants were presented with a physical object, also in the middle of the object size scale to be used. As a final task, participants were asked to complete a questionnaire based on their experience with UsHF (Appendix E).

Procedure

Initially, participants were required to fill out the consent form which also contained questions regarding their suitability for taking part. Participants were asked to put on the headphones and confirm whether they could hear the white noise being played. White noise was played at a volume which masked the sound of the ultrasound array but not the researcher’s voice. Participants took part in a short training period. After the training, participants took part in the size discrimination task. During condition 1, the participant would receive verbal prompts as well as visual prompts as to which object they were experiencing, e.g., 1A, 1B etc. This continued for 33 pairs of objects. Participants would feel the first object, move their hand away from above the array after they were satisfied, they had memorised the size as best they could, and then feel the second object. After experiencing each pair, participants marked an online form (Appendix E) whether they thought ‘A’ or ‘B’ was largest, or whether they thought they were the same size. Though none of the object pairs were the same size, this option was included to discourage participants guessing which object they thought was largest when they may have been uncertain. The same procedure was employed for condition 2, but instead of acclimatisation with UsHF, they were allowed to view and feel a physical object. After taking part in both conditions, participants were asked to complete the questionnaire and were encouraged to be as honest as possible when doing so.

6.3.4.2. Results (Object Size Discrimination Task)

Prior to analysis, the data were subject to inspection via the use of boxplots in order to establish whether there were any outliers. The boxplots did not highlight any outlying data points. As the sample size was relatively small, the data were tested for normality using the Shapiro-Wilk test of normality. The test established that the number of correct answers were normally distributed in both Condition 1 ($p = .970$) and Condition 2 ($p = .124$). As a result, all assumptions for a paired-samples T-Test were met.

A paired-samples T-Test was conducted to establish whether there was a significant difference between object size discrimination accuracy when using 2D visual feedback with UsHF compared to physical objects. Data are mean ± standard deviation unless otherwise stated. The analysis revealed that participants were not able to discern differences in object size as accurately during the UsHF condition (22.67 ± 4.43 correct) compared to when they completed the same task with physical objects (29.67 ± 2.1 correct). The UsHF condition elicited a decrease in size discrimination accuracy (number correct) by -7.00 (95% CI, -8.58 to -5.42). The difference in accuracy during the UsHF condition and physical object condition was statistically significant $t(29) = 9.054$, $p < .001$. *Figure 6.3-4* illustrates this difference.

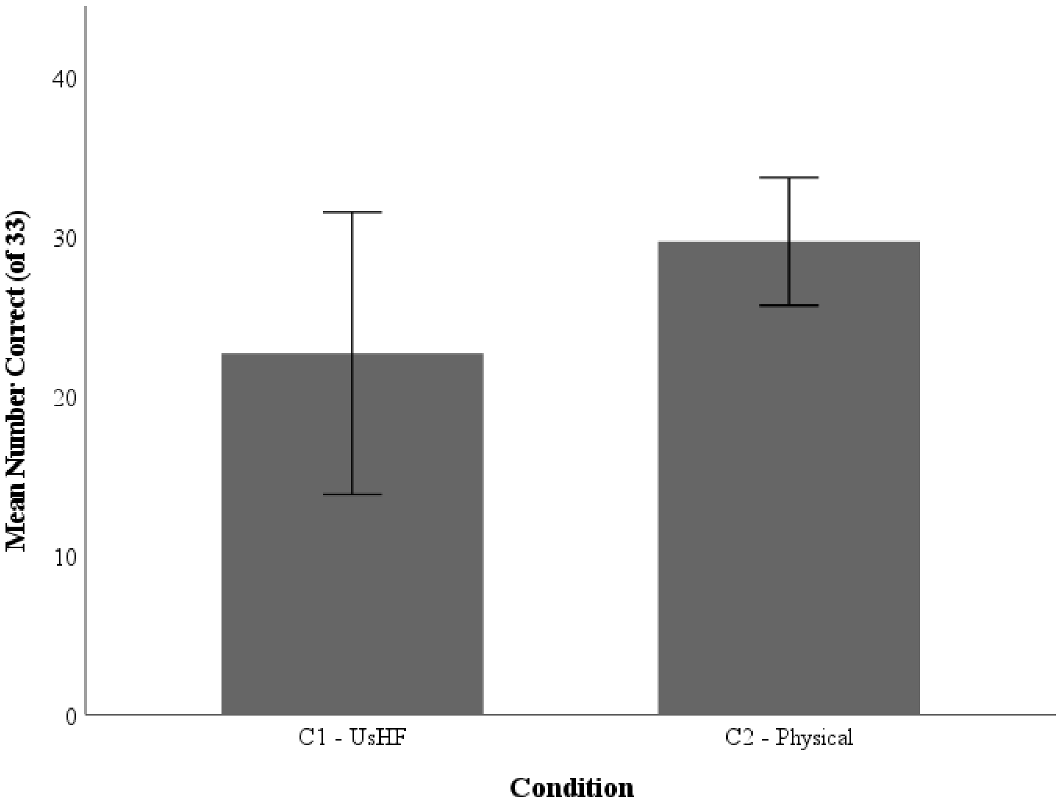


Figure 6.3-4. Illustrates the mean number of correct scores in each condition. Error bars show standard deviation.

Figure 6.3-4 illustrates the significant difference, not only between overall accuracy during both conditions, but also in the significantly lesser deviation in accuracy (as shown by standard deviation bars) during condition 2 compared to condition 1. This suggests individuals are able to determine size differences much more consistently using physical objects.

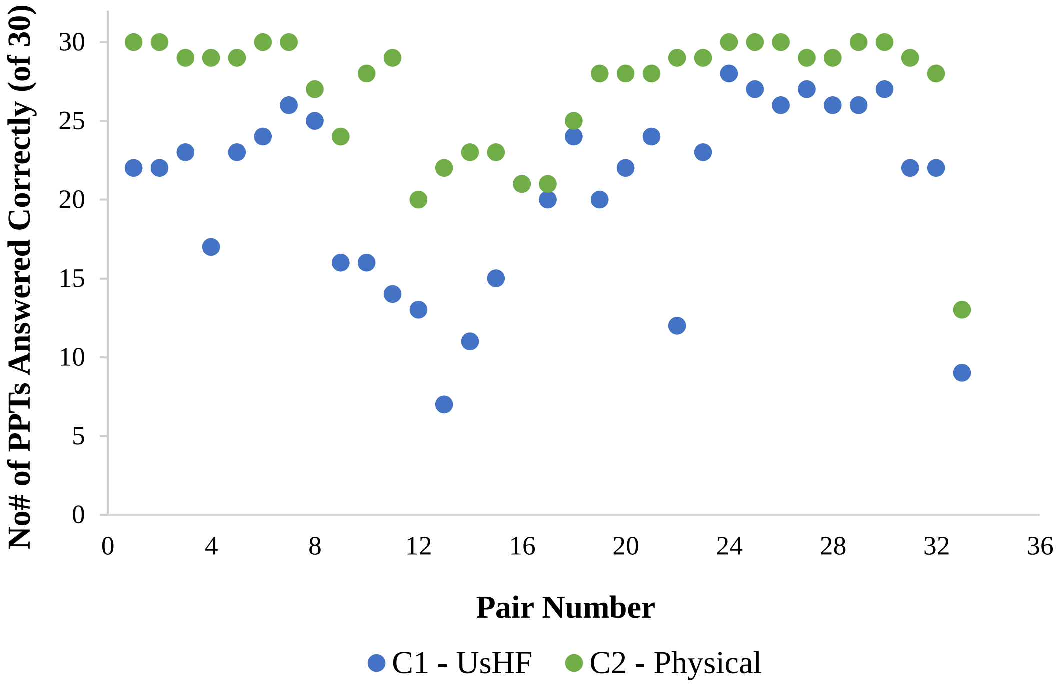


Figure 6.3-5. Chart plotting the number of correct responses per shape pair (of 33) for both conditions 1 and 2.

Figure 6.3-5 visualises like-for-like correct responses for each shape pair during both conditions, allowing for comparisons between the same shape pairs in each condition. The sharp decline in accuracy during pair 33 occurred when discerning object size differences of 15mm. Pair number 1-8 represent objects that were different by 24mm (condition 1) or 12mm (condition 2), pairs 9-22 were objects that differed in 18mm in size, which in turn leads to the decline in accuracy, and pair 23-33 were objects that gradually decreased in size difference (see Table 6.3-2), in theory meaning pair 23 was easiest to differentiate, and 33 most difficult. It is unclear why there was such a sharp decline in accuracy for pair 13 and 22.

6.3.4.3. Results (Questionnaire)

The questionnaire comprised of 11 open ended and 2 closed ended questions which were answered by 29 of the study’s 30 participant sample. The results were analysed using NVivo in order to determine the existence of recurring themes. The closed ended questions were evaluated separately and will be investigated first. Participants were asked in ‘which field they either held a job or were a student within’. 15 of 29 respondents asserted that they were high level (often PhD) students within various engineering disciplines.

The remaining individuals were either students or researchers within the sciences, human factors, or medicine. Finally, participants were asked to indicate whether they had ‘any experience with 3D modelling applications such as, but not limited to Blender and Autodesk’. 19 of 29 participants indicated that they had experience in the aforementioned context. As the majority of the sample are from an engineering background, the remaining responses should hold further value as the technology that is subject of this investigation is poised to be implemented within VR for engineering applications.

The open-ended questions were subject to thematic analysis, the results of which will be portrayed below. Though VR was not implemented during this study, it was important to gain an understanding of participant’s prior experience, particularly with VR. Interestingly, a majority of people had experience within VR, specifically 6 in VR gaming, 1 in engineering applications, 6 via study participation and 5 with general use, leaving 11 with no experience of VR. Question 2 asked respondents whether they believed haptic feedback could improve VR for engineering. 4 and 2 participants were unsure and said ‘no’ respectively, but a vast majority stated their belief in the potential to improve VR with haptic feedback. Rationale for this belief included improvements to immersion and realism (4 and 5 mentions), and improvements to depth perception and general accuracy. The most mentioned improvement can be condensed to a ‘general improvement’ in which individuals believed it would ‘just make the experience better’ or ‘more interesting’ without being able to give much justification.

Exploring participant’s first-hand experience during the experiment, they were asked what their first impression of UsHF was whilst considering any prior expectations. Only one response highlighted perceived ease of use, there were 9 mentions of good, very good and impressive experiences, with one participant stating:

> *“This is the first time I have interacted with UsHF, and I didn't really know how it would feel. But I would say the feeling was very similar to that of air touching my hand. It was interesting to be able to distinguish different sizes.”*

However, a majority of responses highlighted difference in experience compared to their expectations, citing difficulty feeling objects (6) with one participant stating:

> *"It was kind of hard to feel some of the shapes, especially the larger ones. And sometimes I would lose the shape and have to go 'looking' for it again."*

Other rationale for expressing disappointment was that they believed the intensity of the objects to be insufficient (4) and a general difference in the sensation compared to what they expected (3).

With the intention of comparing individual's perceived performance to actual, individuals were asked which condition they believed they were more accurate during, and why they thought that might have been the case. 24 responses indicated that perceived performance was better during the physical condition (2), 4 suggested their performance was better during the UsHF condition (1) and the remaining 1 was unsure. The stated rationale for the preferences towards the physical condition could be a result of procedural issues (though justified earlier), for example:

> *"I was able to discern sizes better with physical objects. This was because I could use points on my hand (like lines on my palms or finger joints) as landmarks to help remember the size, whereas I couldn't do that with the haptic objects."*

However other rationale suggests:

> *"It was much easier when using physical objects as you were able to place them in your hand and hold/feel them in slightly different orientations and within different parts of the hands."*

Conversely, of those who perceived their accuracy to be best during the UsHF condition, one participant said:

> *"I think I was able to discern better UsHF and that is because I would use my expanded hand during the test, allowing me to guess the dimensions of the object according to the different areas/surface it covered in my hand."*

Consolidating findings from the previous question, respondents were asked to give an estimation of their accuracy (% correct) in each condition. Some responses did not adhere to the requested response format, so were excluded. A total of 22 responses were included. See Table 6.3-4.

Table 6.3-4. *The average (mean) perceived and actual accuracy (%) by condition for 22 participants.*

	Mean Perceived Accuracy	**Mean Actual Accuracy**
UsHF (1)	67.4%	68.7%
Physical (2)	86.5%	89.9%

For the next line of questioning, an error occurred which prevented collection of responses from 9 participants, resulting in 20 valid answers. Participants were asked how much they relied on the visual element of size discrimination during each condition. Interestingly during condition 1 (UsHF) participants were evenly split in visual reliance, with 10 suggesting it was used a minority of the time, despite being instructed to pay attention to both haptic and visual stimuli, 9 stating a majority and 1 suggesting the presence of both visual and haptic feedback was confusing. One participant stated:

> *"I tried to not rely on it too much, but my answers would have been more accurate if it had just focused on the visual element."*

During condition 2 (physical), reliance on visual object size discrimination was much higher, with 16 suggesting vision was prioritised a majority of the time, 3 a minority and 1 unclear answer. One participant stated:

> *"I think I relied more on the visual element than for UsHF given that it had an impact on how I approached to hold an object."*

As it was a motivating factor for embarking on this project, participants were asked whether they felt UsHF could accurately replicate physical objects. 17 stated they did not believe so, going as far to say:

> *"I think they are a good approximation, but I would not say they have the quality to replicate physical objects. for me it was easier to feel the external circle, but if I hadn't been watching the monitor with the images, I wouldn't have known the object had a donut shape."*

4 participants stated that they felt the existing setup replicated physical objects sufficiently, with 6 suggesting the technology could replicate physical objects with changes, for example one participant said:

> *"I would probably be able to recognise the shape from UsHF alone, except I found it was hard to distinguish the 'surface' edge/boundary of the object from UsHF."*

Moving on from individual's subjective experience, respondents were asked whether they had any ideas for applications of UsHF. It is worth bearing in mind that as aforementioned, a majority of participants were engineers and have been asked questions regarding haptic feedback for VR in engineering. A majority of responses indicated that they believed the best application of UsHF to lie within entertainment, for example, gaming or interactive attractions. Other notable mentions include disability rehabilitation (3), virtual display buttons (3) and gesture controls (3). Only 2 responses indicated a confidence in UsHF within the field of engineering, for example:

> *"In R&D or Industry, I think it would be an interesting addition when presenting a model/prototype in a wide variety of industries, similarly to 3D printing."*

Finally, participants were asked how they thought UsHF could be improved. A significant proportion of responses (14) included references to improvement of the quality and accuracy of UsHF objects, with several mentions of improvements to the definition of the edges of objects as well as requiring higher/finer definition. Other mentions included improvements to intensity (2), array size (2), surface characteristics (1) and consistency (1). One response suggested the technology did not require any improvements, whilst conversely another response suggested "perhaps it's not even worth investing more into it and one should switch to other technologies".

6.3.5. Discussion (Study 5)

This study consisted of three experiments which sought to establish the following: a reliable method to measure UsHF objects with the intention of scaling physical versions, a paradigm for normalising subjective felt intensity, and establish whether object size discrimination using UsHF was as accurate as size differentiation of physical objects. UsHF measurement revealed that changes of 15mm in the real world. In studying perception of intensity dependent on size (Experiment 1). It was possible to create a set of stimuli that were normalised to feel subjectively the same intensity when using UsHF (Experiment 2). Finally, as hypothesised, the shape size discrimination experiment elicited significantly lower accuracy when using UsHF with visual feedback compared to when using physical objects. As the findings from both experiment one and two of the study are self-explanatory, the findings will not need interpreting, however, the implications of which will be discussed later in this section.

Drawing attention to the main section of this study, experiment three, it can be concluded that UsHF with visual feedback does not offer the user the same level of tactile fidelity as physical objects do (see *Figure 6.3-4*). This in turn leads to lesser ability to discern differences in object size, specifically in this instance, the Outer Diameter (OD) of rings. Not only was the difference in overall accuracy significant, but as was the consistency of users of UsHF compared to physical objects, with a much larger deviation in correct answers seen during the UsHF condition. *Figure 6.3-5* illustrates this point well, highlighting more severe variation in accuracy over the course of the stimuli used during the UsHF condition. *Figure 6.3-5* further highlights this manifestation of low consistency during condition 1, particularly when objects were of smaller size differences (18mm). This was not unexpected, as previous studies, namely Study 3 (Chapter 5) demonstrated that differences of 18mm were not often consistently recognisable by users. However, this serves as an important benchmark when making comparisons to other tactile mediums. On a positive note, though the size discrimination of physical objects was significantly more accurate, it is worth highlighting that considering the extra sensations associated with physical objects that aid the accurate perception of size, namely resistance, object hardness, weight and the ability to grasp, the lesser accuracy in the multimodal condition was relatively close to that in condition 2 on a number of occasions, depending on the stimuli (*Figure 6.3-5*).

This suggests that multimodal UsHF may provide adequate object information depending on the circumstance.

Upon reviewing the data, particularly whilst considering the responses to the questionnaire (which will be explored in more detail during the latter part of this section), it is possible that the inconsistent and lower levels of accuracy seen during condition 1 was due to participants ignoring instructions to pay attention to both the ultrasound haptic and visual information simultaneously. It is unclear why this was, though there are two possible explanations. The first is that users may want to have a 'pure' haptic experience with UsHF. This could be because it is a novel technology and users are more intrigued by it and thus, dedicate more cognitive resources to it. The second possibility is that there is an overload of information, and thus participants cannot process the visual stimuli as well (e.g., Hanson, Whitaker, & Heron, 2009). This theory was supported during Study 4 (Section 6.2) in which accuracy was higher on the same size discrimination task when given visual information alone, compared to the same visual stimuli with the addition of UsHF. This should be explored in more detail.

The questionnaire revealed some interesting and valuable thoughts and interpretations of individual experiences of both the study and UsHF which will serve as a foundation not only for further testing, but also areas the manufacturer could concentrate research recourses towards. As aforementioned, a majority of the sample were from an engineering background, however, despite this, only two thought UsHF would be a valuable addition to VR for engineering applications. Interestingly respondents emphasised a future for UsHF in the entertainment sector, with the technology offering an interesting and relevant addition to games and other interactive scenarios that do not require precision like engineering design does. This attitude is likely due in part to unfulfilled expectations manifesting in a lack of trust in the technology, which in turn results in lower motivation to adopt it. This speculation is indeed supported by the literature and can be partially explained by the expectation confirmation theory, which stipulates the link between expectations and perceived performance and how that can affect desirable outcomes. Indeed, some research has applied this theory to adoption of new technologies, finding that trust in new technologies can be directly influenced by expectations and perceived performance of said technology (Zhang, Yang, &

Robert, 2020). If indeed this theorisation is borne out, users of UsHF will either need their expectations met or exceeded in order to maintain trust in the technology.

Low perceived reliance on the visual element during the UsHF condition and high perceived reliance on visual feedback during the physical condition was a particularly interesting finding, as it directly contradicts data from Study 4 (Section 6.2). Study 4 established what appeared to be over-reliance on visual feedback when paired with UsHF, as when shape A and B were displayed incongruently (meaning individuals were feeling the smaller object whilst seeing the larger), the responses suggested they were using the visual element to inform their choices on which object was largest. Of course, it is possible in the present investigation that although participants did not perceive a reliance on visual feedback during condition 1, that they were subconsciously processing the information. This again could certainly the case during Study 4, wherein accuracy was lower during the UsHF only condition compared to consistent UsHF with visual feedback. As such, these findings should be interpreted with caution.

6.3.6. Conclusion (Study 5)

It is possible to conclude that at present, UsHF combined with visual feedback cannot offer the same level of accuracy in shape-size discrimination provided by interaction with physical objects. Though offering significantly lower size discrimination accuracy occurred during the multimodal condition, it is worthy of mention based on *Figure 6.3-5*, that accuracy did not trail behind that seen with physical objects to a substantial degree in some instances. These findings suggest that although there are limitations in the ability to determine UsHF object size accurately and consistently, the technology may still hold some value within the virtual design process, as supported by some of the qualitative feedback, which highlighted that user attitudes are likely to have an impact on willingness to adopt UsHF for more complex applications, particularly when users cite fears that UsHF may not be accurate or high enough quality for finer work. It is possible that UsHF could be used to indicate collision with virtual objects, rather than to create analogous renders of it. Alternatively to employing UsHF within low-fidelity solutions, future work could look to improve performance of UsHF compared to physical object perception by exploring methods to address issues around visual prioritisation and difficulty detecting mid-air objects, as seen in this study. This has implications for intended applications of UsHF within virtual engineering applications, such as design and prototyping, offering two potential paths of implementation for UsHF.

6.3.7. Limitations (Study 5)

This study was never intended to test real-world interactions with virtual objects, but to examine the usability of UsHF at a basic level. As size perception is paramount for accurate and realistic interaction with objects (e.g., Kristensen et al., 2021; Wing & Wimperis, 2008), size was the focus of this investigation and was indeed an element of previous experiments. As such, it is unclear whether the inaccuracy of size perception using UsHF will translate to poor usability during VR simulations, for example, a scenario in which a designer can interact with a CAD model.

In terms of procedural issues, there was inconsistency in the way in which participants interacted with UsHF objects compared to physical objects. The UsHF object was stationary and only felt from above and slightly from the side, however, physical objects could be picked up and held. This was not an oversight, but part of the design to replicate real world interaction with objects. In reality, interaction with UsHF objects is only possible from the top and very slightly to the side of the object, but physical objects can be interacted with from all angles. It is possible that the results would have been different if participants could only interact with the physical objects in the same way they interacted with UsHF objects. However, in that instance the findings would likely be constrained to the realms of theory, as it would lack real world replicability. Though this is a relevant limitation, it is worth noting that most participants judged the size of physical objects before even making contact with them. Furthermore, it is possible that the addition of the “no difference” option despite there being no shape pairs fitting into that category could have distorted results. However, it was determined that the presence of it would prevent participants guessing which object was largest when they were not sure.

Future work should begin to look at applied implications of the current findings in a real-world VR-engineering scenario, as this was outside of the scope of this study and indeed the project at large.

6.4. Chapter Summary

This chapter was the culmination of all prior research during this PhD, as such it took existing knowledge of the sense of touch as well as knowledge gained from previous chapters and applied it to two final studies which sought to understand how users perceive ultrasound haptic objects. This chapter contained two studies, the first of which (Study 5) aimed to understand how UsHF impacted multimodal perception of object size by using UsHF alongside 2D visual virtual stimuli during a size discrimination task. This chapter concluded with Study 6 which took a multifaceted research approach and first aimed to establish a metric for converting the size of UsHF objects to real-world objects. This was achieved by projecting UsHF stimuli into oil then measuring the objects at the minimum allowable size increments. As all previous investigations highlighted the potential presence of differing subjective UsHF intensity depending on object size, the second part of this investigation sought to create a paradigm for the normalisation of felt-intensity dependent on object size. Finally, part three of Study 6 aimed to determine whether UsHF could adequately replicated physical objects, by comparing ability to discern both UsHF and physical object size differences.

The experiments determined that UsHF did not improve user perception of 2D visual object size, and that there was an apparent bias towards visual object size discrimination during multimodal conditions. It was also found that while UsHF intensity could be normalised across the object size spectrum, that UsHF object size discrimination accuracy was significantly worse than when discriminating physical object size differences. However, it is worth noting that these findings are not necessarily detrimental, and still contribute to knowledge on how best to incorporate UsHF into VR for design. As aforementioned, these findings suggest that UsHF would be best applied to lower-fidelity solutions as a medium to signify contact with virtual objects and to improve subjective experience of virtual environments. Though future work will be discussed in Section 8.7, this speculation should be investigated after a thorough understanding of UsHF perception is achieved.

Chapter 7: Industry Requirements

7.1. Chapter Overview

This chapter presents industry requirements for, and attitudes towards, VR for engineering, whilst eliciting specific feedback on the prospect of haptic feedback, with emphasis on UsHF. This was achieved via administration of remote questionnaires to those within the field of engineering. This approach was employed due to COVID-19 restrictions that prevented both in-person interviews and studies that would have allowed participants to experience UsHF themselves. Instead, users were presented with a description of UsHF and asked to envisage how this technology may play a role within their own work activities.

7.2. **Study 6 –** Industry Requirements and Attitudes Questionnaire

The following sections will explore the basis of this investigation, methods, analysis of qualitative data, culminating in the interpretation of said data.

7.2.1. Introduction and Rationale (Study 6)

VR for engineering design purposes is not a new proposition, with some of the first work in the area occurring during the early 1990s (e.g., Gibson, Brown, Cobb, & Eastgate, 1993; Tanner, 1993), citing VR's potential to replace, or at least compliment the visualisation and prototyping stages of the design process. However, it is only since the 2010s that VR technology has been a viable and ubiquitous technology, not only within the sphere of design, but across several sectors including education, therapy, home entertainment, amongst others. With increased computing power, high resolution of head mounted displays, and affordability through economies of scale, the potential for VR was rediscovered. Many of the benefits VR offers as well as the caveats of VR have been discussed during Chapter 2, so will not be revisited here. While VR technology has only become a widespread design tool in the last decade, VR implementations with haptic interfaces within design are even less common, with examples generally remaining experimental (e.g., Bordegoni & Cugini, 2008). As VR, and VR-haptic interfaces for design are still a relatively underused solution, it is important to understand how it could be implemented to benefit not only the user of the VR, but also the end product.

In order to do this, having an effective ‘requirements’ process is imperative. Requirements can be described as agreed ideas and facts about what a system, solution or indeed a product must achieve and provide its users (Halbleib, 2004). The requirements process is often a separate entity to the other stages of design. It is said that the lack of an adequate requirements process can lead to projects being late, over budget, dysfunctional (Halbleib, 2004), with some suggesting that the absence of such a process is the leading cause of project failure (Kumar, 2006). Though this is not a formal requirements-gathering operation, the purpose of this study was to serve as a foundation for understanding user preferences, attitudes, opinions and potential areas to best focus on the implementation of VR with UsHF. Understanding this will allow future research to be more inclusive of relevant opinion in the field, thus facilitating the creation of VR-UsHF applications that both benefit the user and the output of the design process.

7.2.2. Method (Study 6)

The following section will outline the methods used to collect the data for the current study.

Participants

Participants were recruited according to the criteria that they are currently employed in a job within the engineering design process, but excluding software design. For the sake of this investigation, the engineering design process was defined as "evaluating the problem, researching the problem, choosing a solution, developing a solution, prototyping a solution and testing a solution". Participants were filtered via use of an opt-in button that confirmed their status as part of the aforementioned process. Participants were sourced via the use of ‘Prolific’, an online participant pool of individuals from around the world. A total of 50 participants took part in the current investigation.

The Questionnaire

The questionnaire consisted of a mixture of open ended, Likert-scale and multiple-choice based questions, 13, 6 and 1 respectively, for a total of 20 questions. The full questionnaire can be found in Appendix G. All questions were mandatory, so participants could not skip questions. The questionnaire consisted of four sections and can be summarised as the current design process, the Virtual Reality (VR) design process, improving the VR design process and tactile feedback for VR design. These are the sections that will be referred to when analysing participant responses.

It is important to note that the questionnaire description only alluded to "multimodal VR" and not tactile feedback for VR. This approach was used so respondents were not primed to think specifically about tactile feedback during early questions. The questions were also presented in such an order that tactile/haptic feedback was not mentioned until the final section. This was done in order to establish whether tactile feedback for virtual engineering design purposes was already perceived to be a 'need', before it was mentioned explicitly.

7.2.3. Results (Study 6)

Below, data from four aforementioned sections of the questionnaire will be explored. Analysis of the data will utilise descriptive analysis for Likert-scale questions and Thematic analysis of open ended, qualitative responses.

The Current Design Process

Participants were asked to indicate which option best described their job role. *Figure 7-1* illustrates that a majority of participants had a job role within the research and design stages on the engineering design process, 15 and 17 respectively.

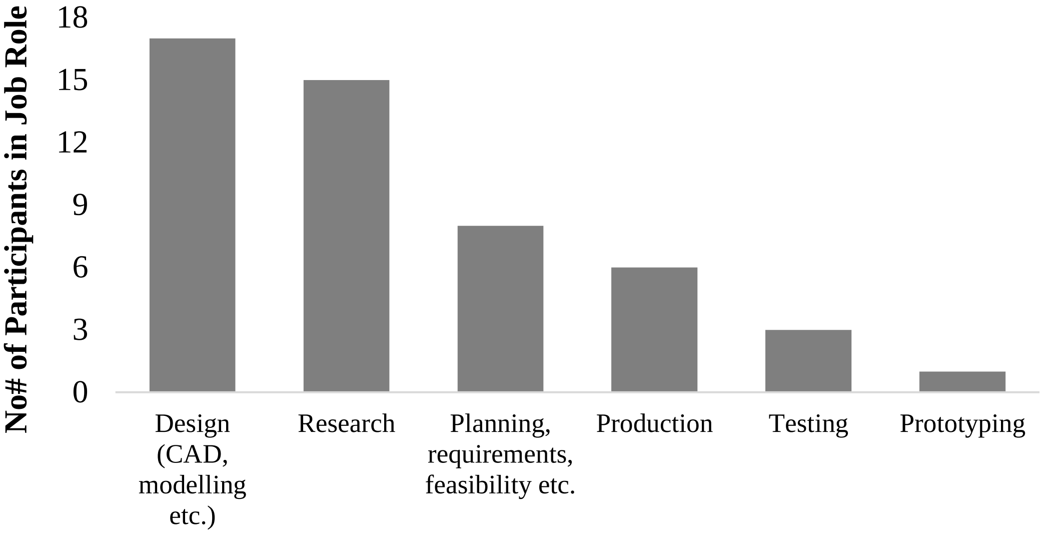


Figure 7-1. “Please indicate which description best describes your job role”.

In order to further understand responses, participants were asked to summarise the general design process they employ.

> *“Define the problem -> do research -> specify requirements -> brainstorm -> evaluate > choose solution -> prototype solution -> test solution” (Participant 11)*

> *“My typical design process follows the 5 Design Thinking steps: empathise, define, ideate, prototype, test.” (Participant 18)*

Many responses reflected the universal engineering design process of “evaluating the problem, researching the problem, choosing a solution, developing a solution, prototyping a solution and testing a solution". A similar answering theme was apparent in 17 of 50 respondents.

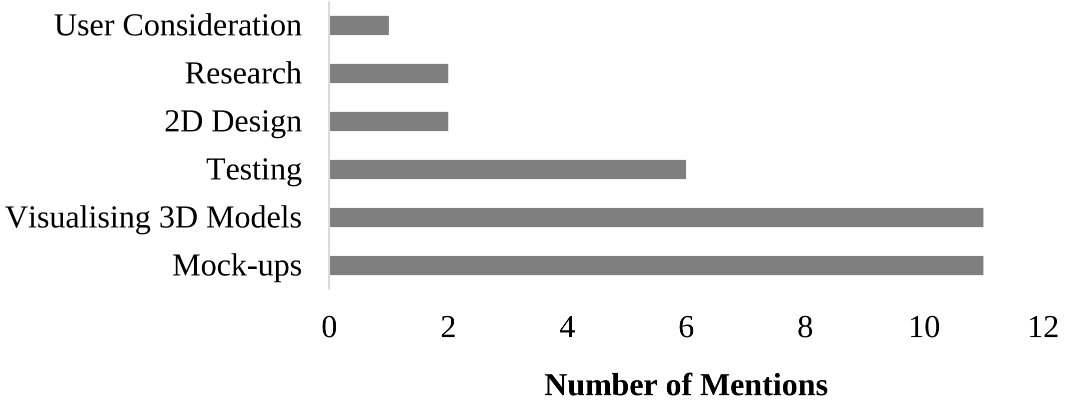


Figure 7-2. “List 3 stages of the design process that could be improved and why”.

When asked to list 3 facets of the traditional design process that could be improved, the top 3 responses were visualising 3D models, mock-ups and testing, with 11, 11 and 6 mentions respectively, as seen in *Figure 7-2*.

Some justifications for the most common answers include:

> *“There are a lot of products on market that aren’t tested enough and its nearly impossible to use it. Consumers don’t want to see product like that” – Testing (Participant 16)*
>
> *“I also wish there was a more direct way of visualising 3D models without having to physically build them (either virtually or in real life)” – Visualising 3D models (Participant 18)*
>
> *“2D and physical mock-ups could be improved to become more sustainable” – Mock-ups (Participant 14)*

The VR Design Process

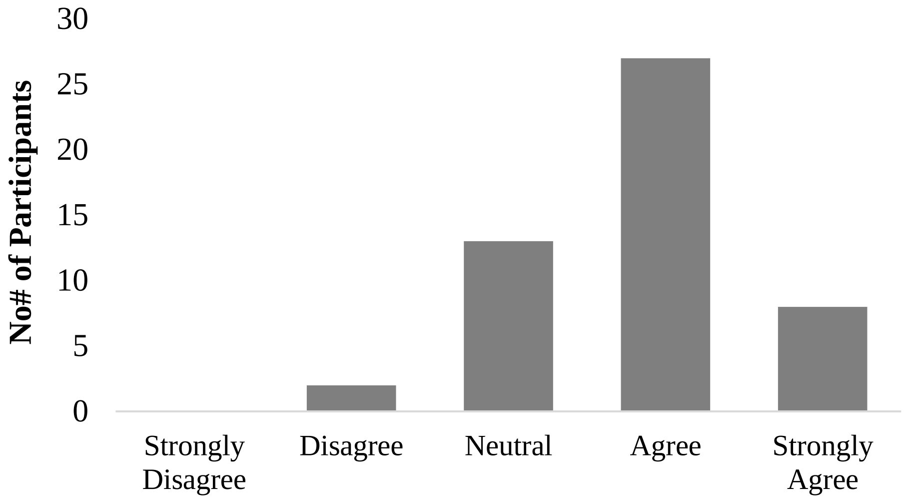


Figure 7-3. “Traditionally physical tasks such as full-size physical mock-ups of designs are witnessing a shift to virtual solutions based within Virtual Reality (VR). To what extent do you feel this is positive for the engineering design process?”.

Figure 7-3 shows that most respondents were in agreement when asked whether the shift of traditionally physical tasks, such as full-size mock-ups to VR was positive for the engineering design process.

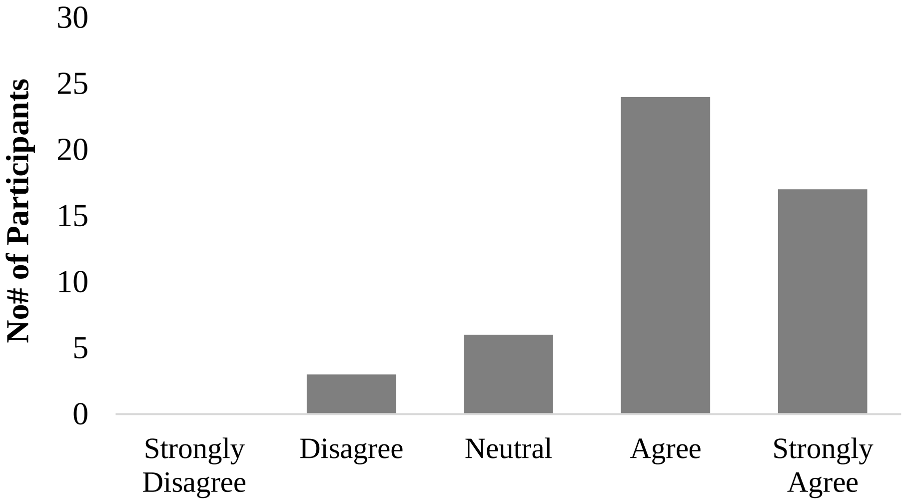


Figure 7-4. “To what extent do you agree with the following statement - The increasing use of VR for the engineering design process improves efficiency”.

Figure 7-4 builds on *Figure 3* by illustrating that a majority either agree or strongly agree that VR for the engineering design process improves efficiency. *Figures 6-3* and *6-4* suggest there is a positive outlook towards VR for engineering design.

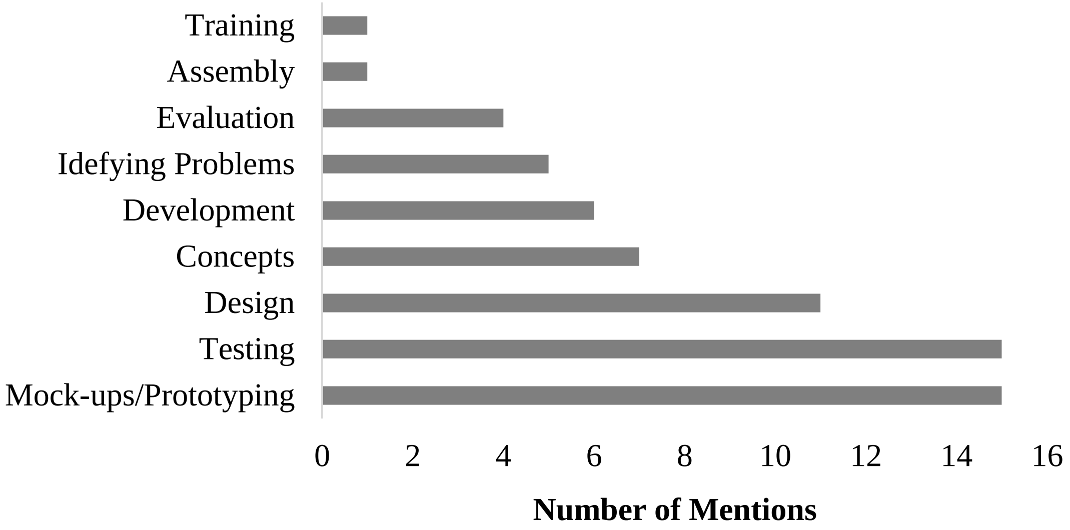


Figure 7-5. "List 3 facets of engineering design process VR is most suited to and why".

Participants suggest that the top three stages of the engineering design process that could benefit most from the use of VR to be design, testing and mock-ups/prototyping. Respondents were asked to expand on this by highlighting what they believed to be both positive and negative aspects of increasing use of VR. Positive feedback suggested that VR could save time, reduce cost and improve collaboration, with one person suggesting:

> *"The main benefit of VR is that [it] will allow people to communicate a problem more effectively and allow testing to be done before a physical mock-up is made, thus allowing engineers to refine the solution earlier on, ultimately saving cost and time."*

Conversely, the predicted negative aspects of VR were increased cost, fatigue or sickness and that it could be misleading:

> *"Detachment from reality. Details like weight or materials might be overlooked for example."*

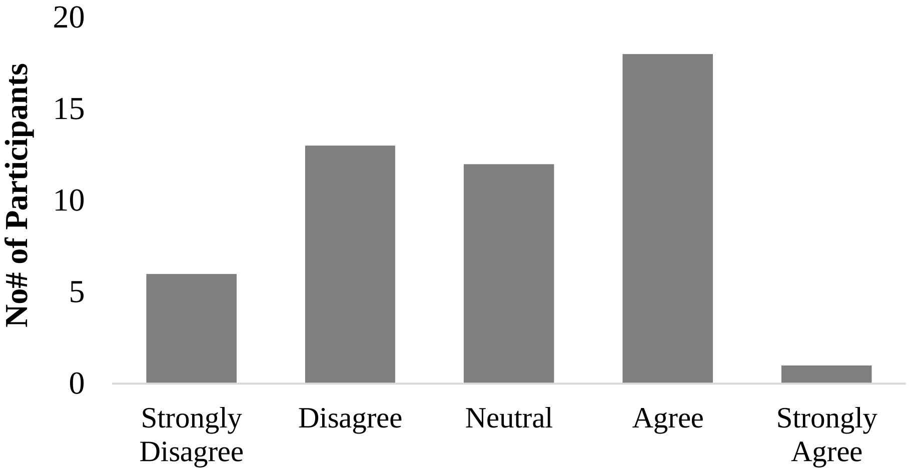


Figure 7-6. “VR for the engineering design process can be subject to some limitations”.

Participants were asked whether they believed VR to have limitations as seen in *Figure 7-6,* which resulted in more neutral and mixed response. Those who agreed that there are limitations with VR suggested that there could be issues with designs too complex for VR, expense of VR equipment, differences between reality and VR and potential side effects of use, limiting the number of people able to use it.

Tactile Feedback for VR Design

This section is focussed on understanding individual opinion on the introduction of tactile feedback to improve VR for design.

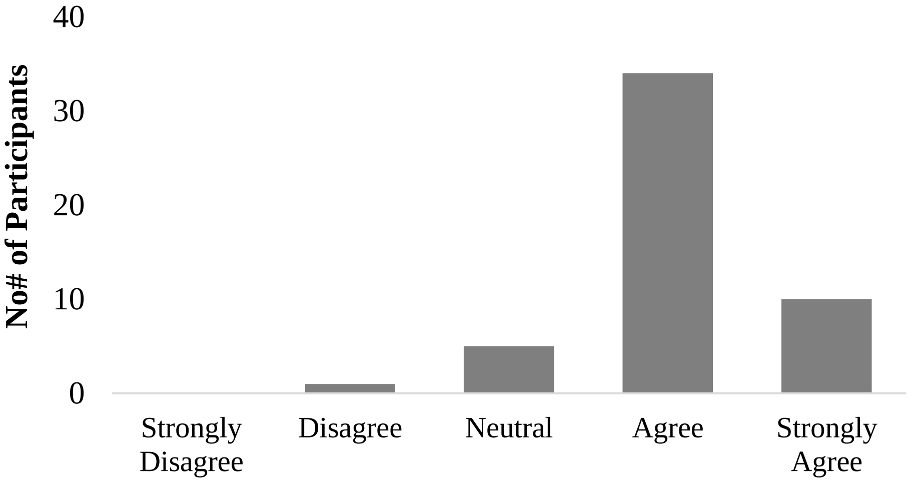


Figure 7-7. “Do you think the presence of technologies to make VR design more realistic would improve the VR design process?”.

When asked whether technologies to make VR design more realistic would improve the VR design process, *Figure 7-7* shows that most respondents either agreed or strongly agreed, suggesting people deem the lack of realism in VR compared to the physical world be detrimental. Participants were asked, without leading, which technologies they believed could improve the realism of VR, the top three subjects in these responses were the implementation of real places/objects (Augmented Reality), the inclusion of tactile feedback and compatibility with CAD.

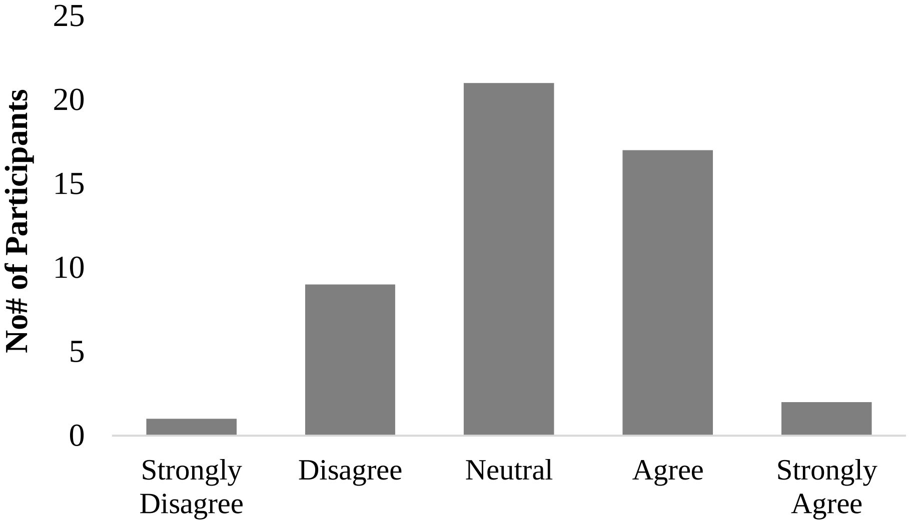


Figure 7-8. “The lack of tactile feedback is detrimental to interaction with VR”.

Participants then indicated whether they believed the lack of tactile feedback in VR to be detrimental to interaction with VR. *Figure 7-8* demonstrates that a significant proportion of people were neutral in whether they believe the lack of tactile feedback in VR to be detrimental. To follow up on this question, respondents were asked whether they believed the addition of tactile feedback to VR would improve interaction during the VR design process (see *Figure 7-9*).

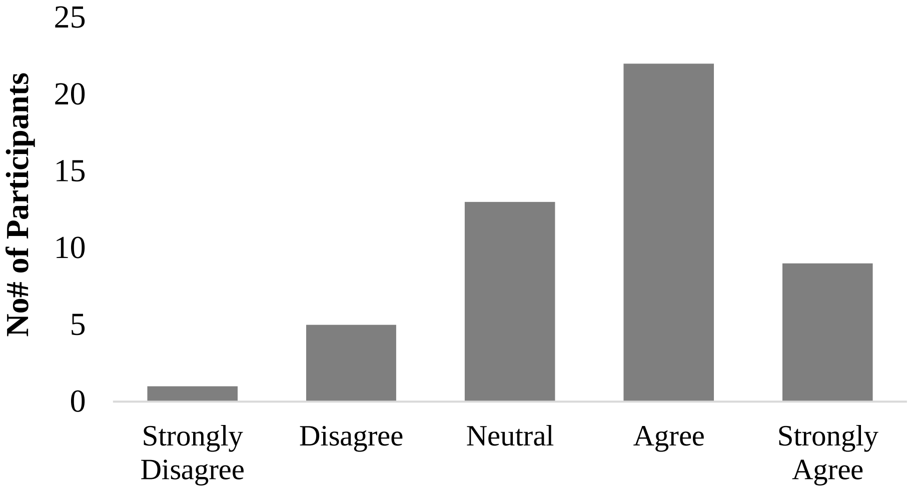


Figure 7-9. “I believe the addition of tactile feedback would improve interaction with VR during the engineering design process”.

Figure 7-9 is notable because it suggests that there is a positive outlook towards tactile feedback for VR engineering design, with most either agreeing or strongly agreeing that such an addition would improve the process. The stated reasons for such agreement saw 13 mentions of improvements to realism, and 8 mentions stating either improvements to accuracy or a reduction in errors when using VR with tactile feedback. This line of questioning was continued to establish which stages of the design process would benefit most from the addition of tactile feedback in VR. Individuals predicted that the testing, mock-up/prototyping, and visualisation/evaluation stages would benefit most. In order for tactile feedback to be most effective during the aforementioned stages, participants were asked what attributes tactile feedback should have, to which most said they should be able to feel surface material, size and object hardness. This question, however, did not yield a high number of responses as per previous questions. Furthermore, participants suggested that tactile feedback would not fully replace physical interaction and that it could have high costs associated with it. Most, however, suggest there would be no limitations.

Ultrasound Haptic Feedback for VR Engineering Design

Finally, participants were given a short explanation of UsHF and what it could offer the user, they were then asked to summarise any pros and cons that could potentially be ascribed to it. Some pros respondents mentioned were that UsHF would improve realism/immersion and would also increase the speed at which users can interact with virtual objects. Cons highlighted concerns of potential health implications associated with the technology, cost, and the lack of detection of object texture using UsHF. Though some answers were given, most did not feel they could comment, likely due to the novel nature of the technology.

7.2.4. Discussion (Study 6)

The current investigation sought to understand the opinions of those in relevant industry positions towards the everchanging engineering design process. Specifically of interest was opinion towards increasing use of Virtual Reality (VR) and the potential to improve VR with the addition of tactile feedback, particularly a new type of tactile feedback called Ultrasound Haptic Feedback (UsHF). The investigation served its purpose and gained some valuable opinion from people in industry, albeit with some limitations that will be addressed later in the discussion.

Most respondents were involved in the design and research phase of the engineering design process (*Figure 7-1*), though the importance of this should not be overemphasised due to many people in industry participating in roles that include several of the options given. Exploring the answers that were given during questioning around *Figure 7-2, 7-3 and 7-4* suggests there is generally a favourable outlook towards VR for engineering design. Furthermore, participants suggest VR is best suited to design, testing, and prototyping tasks (*Figure 7-5*), reasoning that this could allow better communication of design issues to wider audiences, whilst also saving time and money. These responses assume that participants think VR is capable of delivering environments and virtual objects that are realistic enough to use at some of the most critical stages of the design process.

Opposingly, some thought VR would actually increase cost as well as eliciting negative side effects in users, which are equally valid concerns. Hesitancy towards VR because of its potential negative attributes is further highlighted in responses in *Figure*

7-6, wherein the opinion of the presence of limitations is evenly spread. This could be due to lack of direct experience or familiarity with VR, particularly for the application in question. Conversely to the positive outlook observed from *Figure 7-5,* which suggested respondents thought VR was viable in some of the most complex design stages, *Figure 7-6,* and subsequent expansion of answering rationale highlighted concerns regarding whether designs would be too complex for VR and the level of similarity between virtual designs created in physical form.

Importantly for this investigation, the remaining line of questioning addressed participant opinion of technologies used to make VR more realistic. Participants were asked whether they believed the presence of such technologies would be beneficial, and specifically which technologies they believed would improve VR realism. *Figure 7-7* highlights overwhelming agreement that the addition of technologies to enhance the realism of VR would improve the VR engineering design process, further illustrating that some have concerns about the portability of VR designs to the physical world as seen earlier in the questionnaire. They believed this would be improved by implementing real environments and objects in the virtual world, otherwise known as Augmented Reality (AR), tactile feedback and compatibility with CAD software, though it is worth noting that there were only 7, 5 and 3 mentions of the aforementioned solutions respectively.

Focussing on tactile feedback, participants were asked whether they believed the lack of tactile feedback is detrimental to interaction with VR. Most were unsure (*Figure 7-8*), which again is likely due to lack of experience with VR. However, *Figure 7-9* establishes that most people believed the addition of tactile feedback would be beneficial to interaction with VR for engineering design. A likely explanation for these differences is that people do not know whether the lack of tactile feedback makes interaction with virtual worlds significantly worse practically speaking, for example, in ability to grasp objects, but the presence of it would make it more like interactions in the real world, but not necessarily offering improvements. This is likely, as people tend to put more emphasis on the importance of visual stimuli, often forgetting the importance of the sense of touch (Robles-De-La-Torre, 2006). This is supported in some explanations, which state their views are held in the belief the addition of tactile feedback would improve realism, which is a view the literature supports (Ryge, et al., 2017). Some participants also stated that it could also improve accuracy and reduce errors which is also witnessed in many applications of haptic feedback (e.g., Botden, et al., 2008). It is unsurprising that participants asserted the areas that would benefit most from VR with tactile feedback would be evaluation/visualisation, prototyping/mock-ups and testing, all stages which emphasise the importance of feeling designs (Kohtala, Erichsen, Sjoman, & Steinert, 2018). Furthermore, participants were asked what attributes they thought tactile feedback for VR design should have, to which participants responded, surface material, hardness, and size, the former two of which UsHF cannot deliver. Interestingly, some people went so far as to suggest the presence of tactile feedback in VR could not fully replicate real-world interactions, suggesting there could be hesitancy towards haptic technologies. This is notable as attitudes towards technologies will directly influence how readily individuals and companies adopt them (e.g., Roberts, Flin, Millar, & Corradi, 2021).

Finally, participants were introduced to the concept of UsHF. Positively, participants predicted that UsHF could improve the realism/immersion of VR, which could certainly be one of the benefits of being able to ‘walk up and use’ the device with no wearables or prior training. They also predicted it would improve the speed at which people can interact with VR, which is indeed witnessed using other haptic technologies (e.g., Benko, Holz, Sinclair, & Ofek, 2016), but remains to be established with UsHF. However, they correctly believed that UsHF would lack the ability to reproduce the surface textures of virtual objects, something that could be detrimental during several elements of the design process, particularly prototyping and testing. Furthermore, respondents believed there could be excessive costs or health implications associated with UsHF. The costs remain to be seen as the technology is still in its novel phase, however there are a number of people that Ultraleap recommends do not use UsHF, for example, pregnant women, those with implanted medical devices (e.g., a pacemaker), those with heart or hearing conditions and individuals with an impaired sense of touch, whether that be due to age or other conditions. This could exclude a significant proportion of potential users.

7.2.5. Conclusion (Study 6)

Overall, this investigation sought to understand attitudes towards UsHF for VR engineering design. The study highlighted the widespread positive outlook and acceptance of VR and indeed tactile feedback, citing the use of VR to improve sustainability and efficiency, and VR with tactile feedback to improve realism, immersion, and accuracy. The idea of UsHF received mixed responses, with a positive outlook on the potential for UsHF to improve realism and immersion, as well as speed of interaction. However, some also highlighted concerns with potential health issues, cost, and the inability for UsHF to create surface properties of virtual objects. This investigation gave valuable insight into engineer's views on the adoption of VR as well as VR with haptic technologies, highlighting facets of the design process that should be focussed on during future studies, as well as understanding what the technology needs to offer in order for it to be viable on the design process.

7.2.6. Limitations (Study 6)

Due to COVID-19, this study was conducted remotely, using the Prolific online tool to recruit a pool of participants. Unfortunately, it was difficult to verify participants against the very specific requirements for participation, which were planned originally. This issue occurred due to the online nature of the investigation, with no valid way to verify the credentials of respondents, instead relying on their honesty. The result is that some respondents did not provide the quality of responses that were expected, either due to language barriers or lack of knowledge in the field. This meant some responses had to be removed due to inapplicability to the original question. This is evident in the results section as some analysis contains fewer responses. Finally, this questionnaire only sought opinion based either on what the questions told participants, or knowledge already held. It was not possible to establish the baseline knowledge of the subject of focus, which could explain such variance in answer quality. In future, it would likely be beneficial to conduct a similar research of industry participants, but electing for in-person interviews, workshops or focus groups in which participants can experience VR and UsHF before they give their responses. Sadly, due to the pandemic, this has not been possible.

7.3. Chapter Summary

This chapter sought to establish a baseline in attitudes and opinions of industry-based engineers towards VR and haptic feedback for engineering design. This research was determined necessary due to not only the novel nature of UsHF, but also the relative novelty of VR in engineering design. In conducting this work, it was hoped that the results would help form a path for future research and applications of UsHF within engineering design. This investigation gave invaluable insight into the opinions of potential users of multimodal VR within industry, contributing to essential knowledge about what engineers want and need from future technologies that aim to improve engineering design. Generally, it was discovered that engineers were optimistic about the future of VR coupled with tactile feedback for engineering design. The prospect of UsHF was only relatively well received compared to VR, but the data suggest that there was generally a positive outlook towards the technology. This is likely as a result of more people having experience of VR than UsHF. Due to constraints presented by COVID-19 restrictions, participants were unable to try UsHF for themselves and base their opinions on subjective experience, potentially hindering results. However, valuable insight was still gained, with the data highlighting key facets of the design process that engineers believed VR and UsHF could be suited to, thus aiding future research.

Chapter 8: General Discussion

8.1. Chapter Overview

This chapter begins with a summary of the research findings from the four salient areas of investigation. It will then explain how the aims and objectives of this PhD were fulfilled. Thereafter, this chapter will explain the limitations of this research, particularly the effects of conducting the research during a global pandemic. Recommendations for the implementation of UsHF are made before the chapter culminates with a review of the novel contributions with work makes to the field of ultrasound haptics research.

8.2. Summary of Research Findings

This section aims to summarise overall research findings from six studies conducted during the course of this PhD. The findings, themes and interpretation of the data will be explored in detail in the sections thereafter.

Study 1 (Section 4.2) was conducted to establish whether UsHF tactile acuity measured via the use of a mid-air object size discrimination task could be predicted by individual differences in age, gender and hand/fingertip size, as the literature suggested this was a pertinent area of investigation. Whilst there were no significant differences in task accuracy between aforementioned populational differences, the investigation highlighted the need to explore subjective differences in perception of UsHF intensity, which appeared to affect perception of object size, as well as giving an early indication of size difference discrimination limitations.

Study 2 (Section 4.3) built on initial findings from Study 1 and employed a measure of individual tactile thresholds as well as a size discrimination task produced at different intensities. Again, this investigation did not find that populational differences correlated with task accuracy or absolute tactile thresholds. However, it did establish that accuracy during the size discrimination task became significantly worse when objects were projected at lower intensities (40%). Anecdotal evidence collected also suggested that individuals were basing size judgements on perceived intensity. These findings encouraged further investigation into the psychophysical perception of UsHF intensity, but led to the overall conclusion that individual differences in age, gender and hand/fingertip size did not affect perception of UsHF.

Study 3 (Chapter 5) sought to explore in more detail the psychophysical aspects affecting perception on UsHF intensity. This was achieved using stimuli in various combinations that differed in both size and intensity, along with objects that did not differ in size but only intensity. This investigation generated insight into how participants perceive intensity, and highlighted that intensity was oftentimes perceived as size difference. In particular, participants had the propensity to perceive higher intensity objects as being larger. This study also proposed new research questions as to whether intensity could be normalised between object sizes, and how doing so could affect perception.

Study 6 (Chapter 7) aimed to understand the requirements and attitudes of industry towards VR and UsHF for design. Generally, there was a positive outlook towards VR and haptic/ultrasound feedback for engineering applications, particularly within design, testing and prototyping. Conversely, some felt there could be negative elements of UsHF, such as health concerns and the inability to render virtual object surfaces adequately.

Study 4 (Section 6.2) introduced a multimodal element for the first time during this programme of research and sought to establish whether UsHF could improve virtual object size discrimination. It also attempted to understand whether there was a visual/haptic dominance/prioritisation present. It was found that UsHF did not offer a performance benefit compared to a visual only 2D virtual size discrimination task in a multimodal virtual environment. The presence of potential visual dominance was also uncovered.

While study 4 failed to find an objective benefit to the addition of UsHF to visual only simulation, the performance of UsHF vs. physical objects still required investigation. Study 5 (Section 6.3) comprised of three individual experiments: experiment 1 was conducted to establish a measure of UsHF objects for comparison against physical objects; experiment 2 sought to normalise perceived intensity between all object sizes; and experiment 3 employed those normalised stimuli in a size discrimination task comparing UsHF objects to physical replicas of these objects. Finally, this study employed a qualitative element in which participants were asked to share their feedback about UsHF via a series of long answer questions. Experiment 3 demonstrated a significant difference between UsHF and physical object size discrimination, with UsHF eliciting lower task accuracy. Interview responses were useful for determining future directions for UsHF feedback in engineering design applications, for example, for use during collision detection of virtual objects, rather than shape size discrimination.

8.3. Discussion of Research Findings

This section will discuss the research findings, themes and data interpretation from the key research areas outlined below: individual differences, perception of size and intensity, industry requirements and multimodal interaction. The discussion of each area is set in the context of the prior literature. As there is a comprehensive discussion in each study section, this discussion will instead focus on what the findings mean for UsHF and UsHF within virtual design applications.

8.3.1. Individual Differences in Perception of UsHF

There is well founded evidence in the literature to suggest the presence of individual differences in age, gender, and hand/fingertip size on ability to perceive tactile feedback (e.g., Abdouni, et al., 2017; Bruce, 1980; Gallace & Spence, 2014; Kalisch, Ragert, Schwenkreis, Dinse, & Tegenthoff, 2009), with age typically being a predictor of ability to perceive vibration (Verrillo, 1980) which is detected by the same mechanoreceptors (Pacinian and Meissner’s corpuscles) responsible for perception of UsHF (Rakkolainen, Freeman, Sand, Raisamo, & Brewster, 2020). Furthermore, the literature suggests a difference in tactile thresholds with increasing age (Wickremaratchi & Llewelyn, 2006). However, it was unclear whether these differences would manifest during use of UsHF and indeed whether they would influence both subjective and quantitative measures during investigations. External research conducted after studies 1, 2 and 3 seems to corroborate the aforementioned populational tactile differences. For example, when looking at perception of UsHF objects, it was found that increasing age was negatively correlated with shape discrimination accuracy (Rutten, Frier, Van den Bogaert, & Geerts, 2019). This gap in the literature was addressed by assessing whether individual differences in perception of UsHF object size were present during two studies, 1 and 2 (Chapter 4).

Interestingly, and in contrast to the prior literature (e.g., Peters, Hackeman & Goldreich, 2009), Study 1 observed no populational differences in ability to discern differences in mid-air object size. Based on these findings, study 2 sought to explore populational differences in absolute tactile thresholds and introduced UsHF intensity into the shape size discrimination task. Again, and in contrast to what was expected based on the prior literature, age, gender and fingertip area were not found to determine task accuracy in either the shape size discrimination task, or absolute tactile thresholds. After studies 1 and 2, it could be concluded that there were no individual differences present during the use of UsHF for the aforementioned tasks.

There are a number of possible reasons why populational differences did not manifest in UsHF. Firstly, is a question of UsHF fidelity and whether it can produce finite enough differences in the stimuli to illicit populational differences in perception. For example, some studies stipulate that the minimum detectable tactile difference is approximately 0.2mm (Hollins & Risner, 2000), with studies of surface texture perception citing individual ability in discerning texture differences on the micron scale (Miyaoka, Mano, & Ohka, 1999), both of which represent dimensional differences far smaller than UsHF can produce. Secondly, it is possible to speculate that there could be individual differences during different UsHF tasks, though at this stage that seems unlikely. Finally, on a procedural note, it is possible that due to the subjective intensity variation during the early works of this thesis (Study 1 and 2), differences in size perception were masked due to many learning that larger objects felt less intense than smaller objects. Though again, this is unlikely as Study 2 would have highlighted this during investigation of absolute thresholds, which though there were differences between males and females, the deficit was insignificant.

Nonetheless, it is no bad thing that individual differences in the use of UsHF were not observed, as it means that populational differences need not be accounted for during various implementations of the technology, and developers can do so with sound mind that possible usability issues are not due to individual perceptual variation. This is encouraging for UsHF and indeed applications of it within engineering design, but also other applications which may expect a more diverse range of users, such as UsHF for touchless screens and gesture control interfaces.

8.3.2. Perception of UsHF Object Size and Intensity

This is one of the areas of interest that had no foundational literature, meaning the approach adopted was bespoke to this PhD. As such, it is not possible to make comparisons between existing and current work. Though this made investigations more difficult, it led to the discovery of invaluable knowledge of some of the perceptual issues surrounding UsHF.

As shown in Study 1, there was a sharp decline in accuracy for the final 4 pairs of objects, which consisted of object sizes of 48mm vs. 57mm and 51mm vs. 54mm repeated once each. This indicates that a likely replicable limitation in discrimination accuracy manifests when objects differ by 21mm and less. Though limitations in object size discrimination was not a primary objective for study 1, it certainly helped ascertain useful information. Indeed, this had implications for future research and established where populational differences could lie if there were any. This outcome was witnessed again during Study 3 in which accuracy declined significantly when participants were presented with objects which differed between 30mm and 18mm. However, due to the slightly different stimuli set used, it is unclear where the drop off in accuracy occurred, though it is likely the same as seen during Studies 1 and 2 (see *Figure 5-5*).

When evaluating intensity, Study 2, *Figure 4.5-2* demonstrated a decline in task accuracy when both objects were presented at 40% intensity. This demonstrates a clear intensity boundary between 60% and 40% that should not be passed if the user requires mid-air objects that can be easily distinguished in terms of size. It is unsurprising to see a decline in size discrimination at 40% intensity when considering that the absolute detection thresholds for all participants was M = 30.16%, the average for females M = 28.21% and for males M = 31.88%, which is only approximately 10% lower than during the discrimination task during Study 2.

More interesting results were found during Study 3 in which participants were provided with pairs of objects at the same size but different intensity (see *Figure 5-3* and *Figure 5-4*). These results suggest there was a significant impact of intensity on size perception, particularly when one object was delivered using 40% lower intensity than the other, which prompted participants to perceive the higher intensity object as being largest most often. Furthermore, study 4 (Chapter 6) established in a rudimentary capacity that subjective intensity could be normalised for different size objects, though there still appeared to be a deficit when testing the normalised stimuli during the size discrimination task.

The results pertaining to limitations in size and intensity perception were not known before this work took place and are important as they have implications for applications of UsHF, particularly within virtual design. As it stands, perceived intensity is one of the most apparent contributors to psychophysical differences in virtual object perception, and as such, need to be considered in a manner appropriate to the application of UsHF.

Firstly, it is possible that size perception of virtual objects could play a key role in the recognition and manipulation of virtual objects (Wing & Wimperis, 2008) however, on the contrary, it is also possible that perception of object size has no bearing on those activities, as, for example, simple vibrotactile feedback can be seen to benefit improve distance estimation (Abdullah, Lawson, & Roper, 2017). In the former instance it is important that implementations of UsHF scale properly to the application, which will take time. It is also essential that implementations of engineering design take the limitations in size/intensity perception into account when creating solutions. It is possible that future research could create a model for this. The latter example of simplified haptic feedback could be a benefit in a number of instances, which would facilitate simpler implementations of the technology, this will be explored below. If indeed perception of object size is essential in VR for engineering design, UsHF as it stands could create perceptual issues between visual and haptic stimuli, and thus, negatively impact trust and willingness to use UsHF.

As UsHF intensity appears to be a powerful attribute to manipulate perception of object size, it could be used to the benefit of developers in facilitating less complex implementations of UsHF. For example, in a virtual CAD environment it could be possible to alter perceived intensity to mimic dimensional differences rather than rendering analogous virtual objects. However, viewed pessimistically, subjective variation in the interpretation of UsHF intensity could be very detrimental to users, as it could be confusing and lead to distrust of the interface.

8.3.3. Multimodal Interaction with UsHF and Sensory Dominance

The literature states the importance of multimodal virtual environments in order to enhance the authenticity of the VE and the user's sense of immersion (Burdea, Richard, & Coiffet, 1996) as well as improving interaction with virtual objects (Nizam, et al., 2018). Whilst the overall focus of this PhD was to explore the human factors elements of UsHF and not multimodality exclusively, there are inherent limitations on the assertions this work can make with regards to UsHF in a multimodal context. However, multimodality was explored in some detail during Study 4 (Section 6.2) and Study 5 (Section 6.3).

Study 4 (Section 6.2) gave initial insight into how multimodality affects perception of object size when combined with UsHF and offered some interesting results. Looking at *Figure 6.2-2* the effects of multimodality are apparent, wherein there was no significant difference in object size discrimination between haptic only and haptic and visual (congruent). Also notable is the high degree of accuracy in the visual only condition, which was significantly better than haptic only condition, but not the haptic and visual (congruent) condition. These results suggest that UsHF did not improve accuracy of shape size perception, and that visual only size discrimination was most effective. This is corroborated in the literature to some extent, wherein some authors suggest that vision dominates as it is often the most reliable sense (Spence, 2016).

These findings were also corroborated by Study 5 (Section 6.3.4) in which users were presented with a multimodal size discrimination task and a physical size discrimination task. The accuracy seen during physical size perception was significantly better than that seen in the visuo-haptic condition, with the visuo-haptic condition also eliciting much greater variation in accuracy during the trial (see *Figure 6.3-5*).

Due to the fact that evidence from the literature suggested the occurrence of visual dominance under some circumstances (e.g., Botvinick & Cohen, 1998; Gibson, Brown, Cobb, & Eastgate, 1993), this was also an area of investigation, and as such utilised stimuli that could shed light on whether visual dominance during the use of UsHF is apparent. This was achieved by introducing contrasting visuo-haptic stimuli, for example, the pairs of objects during condition 4 of Study 5 were flipped, so whilst the largest shape was on screen, the smallest shape was delivered via UsHF, and vice versa. When participants were asked to select which object they thought was largest, it should demonstrate which medium dominates the other, or even which they trust more in that situation. This condition yielded the lowest number of correct results, which allows for some inferences to be drawn. It suggests that indeed, participants prioritised visual stimuli over haptic stimuli, which could allude to diffused trust in UsHF, or simply that it was a natural and automatic prioritisation of visual stimuli. The reasoning remains unclear, but it does have implications for future applications, particularly within engineering design. Firstly, it suggests that the presence of conflicting stimuli can have a detrimental effect on object perception, which could cause confusion and unwillingness to use UsHF. This means it may be essential to conduct thorough testing of perception on an application-by-application basis. Developers should be aware of this occurrence as it could have a negative impact on solutions involving UsHF and it may take time to correct for perceptual issues in individual instances. Secondly, it brings into question whether UsHF offers sufficient tactile feedback to foster trust and acceptance of the device within the context of VR for engineering design, wherein perception of intricate object detail is necessary. On the latter point, it is worth noting that this research does not provide a concrete basis for that speculation, but instead proposes that question is researched in future studies. Furthermore, the inability to replicate physical objects witnessed both in the quantitative and qualitative data raises further queries about the usefulness of UsHF in design, and as such means the justification of UsHF for that field cannot be made on the basis of improved accuracy over physical prototypes, for example. What does need to be considered is the level of haptic accuracy that is required for any given application. This is something that is explored in the following section (8.4.4). Both studies 5 and 6 contributed to knowledge of how users perceive multimodal-UsHF applications, and thus, how users may prioritise multisensory feedback.

8.3.4. Industry Requirements and Attitudes Towards UsHF and VR for Engineering

Design requirements at an early stage of a new technology implementation and the general design process are thought to be essential, with some positing that failure to enact an effective requirements process can negatively impact the future design and implementation phases (Halbleib, 2004). As such, it was deemed necessary to gather rudimentary requirements, attitudes and opinions of both industry participants and users during the early stages of UsHF research and implementations. This was conducted during both Study 5 (Section 6.3) and Study 6 (Chapter 7).

Study 6 (Chapter 7) surveyed individuals with roles in the engineering industry and sought to understand their views towards VR, haptic feedback and UsHF for engineering design. This research demonstrated that there was an impetus to improve the design process with additional technologies like VR can make the process easier, more efficient and improve the final product, with most suggesting that the shift towards VR in place of physical mock-ups and prototypes to be a good thing. However, some responses were mixed in their optimism. Most suggested that there was a relevant place of VR in the design process, particularly within prototyping, testing, design and visualisation, but others suggested that the use of VR could introduce other usability issues into the design process, for example, cost, fatigue, simulator sickness and inconsistencies between VR visualisations and the final product.

In order to combat some of these issues, the questionnaire proposed the addition of tactile feedback to improve interaction with VR, which a vast majority perceived to yield improvements. UsHF was also a relevant line of questioning, though it was not emphasised as the respondents would have had no experience with the technology, so more intricate lines of questioning were not required. On a positive note, many thought UsHF could improve immersion and interaction efficiency, whereas some highlighted foreseen issues such as cost and the inability to portray surface textures using UsHF.

The qualitative element of study 5 (Section 6.3.4) built on this by surveying actual users of the technology, a majority of which were from the engineering sector. Initially many cited that their experience of UsHF was good, however, a majority suggested their interaction with UsHF was different to what they expected, citing issues with locating and perceiving mid-air objects. Interestingly, most suggested they did not believe UsHF could accurately replace physical objects, stating that UsHF creates a good “approximation”. Though some were more optimistic in their ability to discern object sizes with UsHF alone, particularly if the edges of mid-air stimuli could be more defined.

On a positive note, many people corroborated the position of this thesis by suggesting that UsHF would suit VR for experiencing engineering prototypes, but not so much for the creation and alteration of designs, which is still a valuable addition to the design process in order to reduce production time, cost and waste. At present, Study 6 highlights the improvements to UsHF required in order to apply it to more intricate design phases, such as improved fidelity and accuracy of mid-air objects, particularly pertaining to edge definition, as well as increased intensity and improved surface characteristics, though the latter is not likely possible due to innate limitations of using ultrasound to induce tactile sensations. Considering these findings, it is further possible to assert that the role UsHF could play in VR for engineering design is one that improves immersion and general experience of early VR design phases. Implementations within industry should therefore be carefully managed by ensuring aforementioned concerns are addressed for the technology to be an effective and beneficial tool.

8.4. Review of Aims and Objectives

This section will review whether the original aims and objectives stated in section 1.4 were satisfied and explain briefly how this was accomplished.

8.4.1. Review of Aims

Aim 1 - Investigate the human factors issues surrounding UsHF

At the time of writing, though there is considerable research into the human factors related elements of haptic feedback, there is currently only one piece of literature that explores human factors considerations for UsHF (e.g., Rutten, Frier, Van den Bogaert, & Geerts, 2019). This aim sought to address this literary deficit by exploring the human factors of the perception of UsHF stimuli. This aim can be considered successful through the achievement of specific objectives, outlined below, but more generally through a human centric approach to the research itself, by taking individual feedback into account before progressing to subsequent stages. Moreover, in line with a human factors approach (Wilson, 2005), the research was not purely theoretical or human science based, but also considered the practical application of the work, in this case, engineering design.

As a result, investigation of human factors issues was a theme permeating throughout this work. Furthermore, measures that were used were selected with the human factor in mind. Due to the novel nature of UsHF, the overall aim during was to investigate the viability of the technology in a nuanced fashion, with a particular emphasis on perception of mid-air stimuli and its various characteristics that can affect perception, such as intensity and object size. This was achieved by employing measures of tactile perception of UsHF, such as mid-air object size differences, absolute tactile thresholds and UsHF intensity. Furthermore, qualitative measures of the human factor were bolstered by considering user opinion and acceptance of the technology.

Aim 2 - Understand whether the presence of UsHF can be beneficial to interaction with virtual objects during engineering design applications

This aim can be considered in light of the specific objectives, which are reviewed below. However, achievement of this specific aim was impacted by two factors. Firstly, the course of this research spanned the COVID-19 pandemic, which means that the original intention of more in-depth research within engineering firms was hindered as companies had to prioritise their efforts on core business, and travel restrictions affected researcher mobility. Secondly, it became apparent that more fundamental research was needed in individual differences, intensity, UsHF object size discrimination and multimodal sensory dominance to underpin more practical application within engineering companies. Nonetheless, this aim has been achieved through research, in particular Study 5 (Section 6.3), a survey of engineering designers and Study 6 (Chapter 7) which queried users of the technology, a majority of which were based in engineering within academia.

Aim 3 - Determine whether the absence of kinaesthetic feedback is detrimental to user perception of mid-air objects

This was quite clearly demonstrated to be the case through Study 5 (Section 6.3), which showed significantly worse scores for object size discrimination in UsHF vs. real objects. However, despite this performance detriment attributed to lack of kinaesthetic feedback (which physical objects provide), the data showed that UsHF does offer potential advantages in other measures, such as subjective feedback on usefulness for design, and as a possible mechanism to improve the realism and immersion of VR experiences. Though this aim was satisfied through the aforementioned measures, it does not stipulate certainly how these findings will transfer to applied versions of a VR-UsHF interface.

Aim 4 - Explore whether UsHF objects can offer sufficient accuracy to replace physical objects in design tasks

Building on Aim 3, it can be concluded from the research conducted during this PhD (Study 5, Section 6.3) that UsHF cannot offer sufficient accuracy to replace physical design tasks, thus satisfying this aim. This is evidenced through both measures of size discrimination accuracy as well as feedback from engineering-based participants who casted doubt on whether the technology could replace physical elements of the design process. Optimistically, some suggested that whilst UsHF could not likely replace the more physical stages of the design process, it could offer benefits in VR visualisation and evaluation of early designs, achieved either through simple collision notifications with virtual objects or simply to improve the immersion of a VR evaluation environment.

Aim 5 - Understand industry attitudes towards engineering related applications of VR and UsHF

This aim was satisfied during qualitative research during both Study 5 (Section 6.3) and Study 6 (Chapter 7). Through this research, insightful opinion and feedback was gathered from both industry-based and academia-based engineers who cited general acceptance and willingness to adopt VR for design, as well as implementations of VR with haptic feedback to improve immersion.

8.4.2. Review of Objectives

Objective 1 - Investigate individual differences in UsHF object size perception

This objective was satisfied during Study 1 (Section 4.2) and Study 2 (Section 4.3) by investigating tactile acuity by looking at UsHF object size discrimination. The lack of identifiable individual differences in aforementioned measures as a function of age, gender and fingertip/hand size mean that implementations of UsHF are likely to be simplified as they do not need to be designed to cater for variation in populational differences in UsHF perception.

Objective 2 - Investigate the populational differences in tactile thresholds when using UsHF

This objective was addressed during Study 2, finding that there were no significant population differences in absolute UsHF tactile thresholds whilst establishing that the minimum detectable UsHF stimuli to be ~30% percent intensity on a mid-air object of 57mm in size.

Objective 3 - Conduct experimental research to understand user perception of UsHF intensity

This objective was satisfied thoroughly as intensity perception took centre stage during investigations due to its apparent propensity to affect perception of object size. Enquiry into the effects of intensity on user perception was conducted during Study 2 (Section 4.3), Study 3 (Chapter 5), Study 4 (Section 6.2) and Study 5 (Section 6.3). Size discrimination accuracy was found to decrease significantly at 40% intensity and when given shapes of the same size but of differing intensity, users perceived a difference in size that was not there. This research demonstrates UsHF intensity, which was previously unexplored, to have a significant impact on how users perceive mid-air objects.

Objective 4 - Study multimodal perception of virtual object size

Objective 4 was explored during Study 4 (Section 6.2) and Study 5 (Section 6.3) during the former, users were given an object size discrimination task both with and without multimodal feedback, and the latter, multimodal size discrimination was pitted against physical object size discrimination. The results demonstrated that UsHF did not offer any benefits to visual, virtual size discrimination, but also did not hinder accuracy to a significant degree during the task.

Objective 5 - Examine differences in size perception accuracy using UsHF with virtual objects compared to physical objects

This objective was satisfied during study, 5 (Section 6.3) in which tactile accuracy in object size discrimination using multimodal UsHF was compared to physical object size perception. It was found that physical object size discrimination was significantly better than visuo-haptic size discrimination, with some citing increase confidence in physical objects and overreliance on the visual element during the visuo-haptic condition.

Objective 6 - Administer questionnaires to study participants and wider industry respondents to gauge attitudes towards UsHF and multimodal VR for engineering applications

Finally, objective 6 was satisfied during Study 5 (Section 6.3) and Study 6 (Chapter 7) by administering questionnaires to individuals in the engineering industry and users of UsHF respectively. Findings suggested a positive outlook towards VR and haptic feedback for design, though some were critical of UsHF as a tactile medium. This can be explained in part due to the remote nature of the study wherein none of the participants had direct experience with UsHF. Study 6 highlighted a more positive outlook towards the technology, but some were critical and offered solutions to improve it for engineering design.

It can be concluded that all aims and objectives proposed for this PhD were satisfied, though some require more research to offer concrete evidence and recommendations for implementation of UsHF.

8.5. Limitations of the Research

In terms of the experimental research, there are some limitations on the inferences that can be drawn for engineering design due to the controlled nature of the experiments. As mentioned prior, it is not possible to know whether the human factors concerns will be replicated in an applied setting without testing. In terms of qualitative research, the research was limited in who could take part, this was due to the COVID-19 pandemic restrictions, which will be summarised below.

8.5.1. Comparing UsHF to Physical Objects

This section alludes specifically to Study 5 (Section 6.3). In summary, Study 6 investigated size discrimination accuracy between UsHF with visual feedback and physical replicas of the same virtual objects. Naturally, interaction between virtual and physical objects is different, highlighting some limitations with this methodology. The key differences in interactions between the two mediums are that the UsHF stimuli did not have a virtual hand as a reference point and that they were stationary above the array, whereas the physical objects could be picked up and grasped and participants could use their hand as a size guide, though the latter was not instructed. Though this was an intentional part of the design, it could have impacted the data.

As is known, body-based-scaling is a widespread phenomenon in both the physical world and with VR interactions (see Section 3.2.1), and states that the size of virtual bodily reference points can have a significant impact on perception of virtual objects. As such, it was determined that the presence of avatars or hand representations would have introduced a higher degree of uncertainty in the data than in the absence of such features. However, there is an argument to be made that the presence of such a feature could have improved presence and subsequent interaction with virtual objects (Jung, Bruder, & Wisniewski, 2018).

In terms of object grasping, there is an inherent limitation with UsHF in terms of the axes object interaction can occur in. For example, grasping a UsHF object and rotating a flat hand 90 degrees will result in no haptic feedback in the area of the hand the object is grasped within. It is possible that making interaction with physical more analogous to UsHF could have yielded more comparable results, however, this would not have been how users would interact with a physical prototype in the real world, so could have diverged further from a good lab-reality balance. It is not clear whether the aforementioned elements of the study design have hindered results, it is worth considering these design features during future work.

8.5.2. COVID-19

Restrictions associated with the COVID-19 pandemic started approximately halfway through this PhD (March 2020) and continued, for the most part, the remainder of the PhD which had a profound effect on the research that could be conducted for this thesis. Experimental research ultimately had to be simplified due to time limitations once we were given clearance by the University to recommence human trials. Plans to hold workshops with industrial partners were put on hold and ultimately cancelled due to restrictions, meaning that most of the qualitative research had to be conducted via an online and theoretical basis, as opposed to being able to demonstrate the technology to engineers and receive their direct feedback.

8.6. Recommendations

This section will briefly summarise findings, guidelines and future work in tabular format before being explored in a more comprehensive manner in the following sub-sections.

Table 8.6-1. *This summarises some of the key findings, guidelines and associated future work.*

Key Findings	Guidelines	Future Work
	Size Perception	
Size differences of 21mm and less yield a sharp decline in discrimination accuracy	Maintain object size differences above 21mm if accuracy is a primary consideration	Establish whether accurate UsHF size perception affects task accuracy, efficiency and speed
Size discrimination of UsHF objects in a multimodal 2D environment is not as accurate as physical object size discrimination	If applied to virtual engineering design to replace physical prototypes, UsHF should only be applied to early design stages which do not rely on high fidelity renditions of virtual objects	Explore whether the results found are borne out in immersive VR with UsHF in order to directly compare to a realistic use case

Intensity		
Object intensity has a significant influence on perception of object size	Ensure object intensities are normalised for various object sizes	Understand whether stimuli of the same size but varies intensities can serve as a medium to convey object size information in immersive VR
Accurate detection of stimuli significantly decreases when objects are displayed at intensities below 60%	Stimuli should not be displayed below 60% in order to maintain reliable perception	Explore whether stimuli produced at <60% can still convey an illusion of size change
Sensory Dominance		
Bias towards visual stimuli was witnessed during size discrimination tasks in multimodal scenarios	If employing an implementation requiring accurate portrayal of object size, emphasise the UsHF element less by using it as to compliment visual stimuli rather than to convey all object information	Visual dominance is a common phenomenon depending on the stimulus. However, it should be established whether this bias affects interaction with UsHF

8.6.1. Recommendations for Implementations of UsHF

Study 1 – Found an early indicator of mid-air object size discrimination limitations, as such, it is possible, based on these findings to recommend in future applications, that objects that differ finitely in size (in this instance by 21mm) and below are not used in order to preserve discrimination accuracy.

Study 2 – This investigation focussed on size discrimination at different intensities. The findings suggest size discrimination to deteriorate significantly between 60% and 40%. As such, it can be recommended that stimuli should not be projected at intensities lower than 60% in order to maintain size discrimination accuracy. It also found absolute tactile thresholds to lie around 30%, after which participants could not effectively perceive stimuli. This means when accurate size perception is not a requirement, stimuli could be projected as low as ~30%, however, this is not recommended, due to perceptual inconsistencies that are likely to arise. Developers should refer to the previous limitations as a guide for minimum applied intensity.

Study 3 - This investigation sought to establish how UsHF intensity can affect perception of object size. The results demonstrate that intensity alone can have a significant impact on user's perception of object size. As such, recommendations can be made with regard to normalising subjective intensity for different size/types of objects. Alternatively, it is possible to suggest that simply giving short bursts of the same size object, but of varying intensities can be used to illicit perceived differences in size, which could be useful in signifying contact with virtual objects.

In this instance, it is possible to recommend that in portraying larger objects, a higher intensity can be used, and a lower intensity can be used for smaller objects.

Study 4 – This was the first investigation into multimodality. Results suggested that multimodal (visuo-haptic) was not more effective than vision only during a size discrimination task, though it was also not significantly worse. It also found that participants prioritised visual feedback, suggesting discrepancy in what is viewed on screen compared to what is felt via UsHF can be detrimental. Thus, if developers want to implement multimodal UsHF interfaces, it is important that what is seen on screen is also *felt*, as failure to do so could cause inaccuracy and potentially distrust of UsHF. This is likely to be a time-consuming task and gives further credence to the earlier suggestion that UsHF should be used as an indicator for interaction with virtual objects rather than attempt to replicate them exactly.

Study 5 – This study consisted of three experiments, two of which will be referred to in this segment. Firstly, it was demonstrated that subjective intensity between object sizes was possible. Secondly, it demonstrated that size discrimination of physical objects was significantly better than multimodal UsHF. Finally, based on user feedback, many deemed that the technology would be best suited to less tactile elements of the design process, such as visualisation and evaluation of designs. It is thus possible to recommend that size-intensity normalisation is carried out early on in a UsHF implementation. Both the findings from the second and final elements of the study suggest that UsHF is not able to accurately replicate physical objects, and thus, implementations should focus on early design stages such as initial evaluation and visualisation to improve the VR experience.

Study 6 – Gave a great pretext for offering recommendations for the implementations, as the recommendations came straight from industry-based engineers. Though the questionnaire did not focus on UsHF as much as general tactile feedback, opinions suggested that the best areas of application for VR with haptic feedback to be within the design, testing and prototyping. This gives a clear indicator of where best to focus research resources for UsHF within engineering design.

8.6.2. Recommendations for Future Research

This thesis by no means claims to be the work to begin and end all human factors-UsHF research, as such, this is an area that still requires thorough investigation before and if the technology becomes widely adopted. Below is a summary of key knowledge derived from this research (see Table

Size Perception

In terms of UsHF object perception, future work should establish whether object size perception is relevant to UsHF applied in a 3D VR environment, this could be achieved by adopting a similar methodology as seen in Study 4 (Section 6.2), in which users are given conflicting visuo-haptic information in order to determine stimulus prioritisation for judging object size, in turn establishing whether UsHF is relevant to the size perception process. This could also be achieved via studies of the same size perception task which could utilise VR with and without UsHF, which would determine whether size discrimination is better, worse or the same. This is important, as the research proposed during this thesis appears to suggest the presence of UsHF not to be beneficial to size perception of virtual objects.

Stimuli Characteristics

Future research in terms of stimuli perception should explore the perception of object characteristics themselves, for example as Rutten, Frier, Van den Bogaert and Geerts (2019) did, by exploring accuracy of object type perception using only UsHF. These types of study are required in order to understand whether on a general and populational level, users can be provided with accurate virtual object renditions via UsHF. This could be achieved by firstly analysing populational differences in the perception of object characteristics, such as gender and fingertip/hand size, as age seems to play a key role in object determination (Rutten, et al., 2019). If indeed there are widespread populational differences in perception of objects, as observed by Rutten et al. (2019) in a VR-UsHF interface, it would have considerable implications for the technology and future implementations.

UsHF Intensity

In terms of UsHF intensity, human factors investigations would benefit from further exploration of the already well-established psychophysical differences in UsHF intensity perception found during this work. For example, by understanding how intensity can be used to emulate object size for collision detection rather than emulating the entire object. This is likely a valuable area of investigation as UsHF does not have the capacity to give continuous object feedback to a user once an object is grasped, for example, this is due to the fact that the palm would not be open to receive tactile feedback.

VR-UsHF Observations

Future research should, in a detailed fashion, investigate the possible benefits and drawbacks of using UsHF in 3D VR, for example, whether it affects reaching to grasp objects, grasping and general manipulation of VR objects. This could also be extended to investigate the effect UsHF has on 3D VR design tasks, for example, visualisation, evaluation and assembly simply by having conditions with and without UsHF.

Qualitative Investigations

It could also be proposed that future studies include a qualitative element to establish user preferences and feedback after each experiment, as this will help researchers and developers alter experiments and implementations based on subjective feedback. It is likely worth creating a rating scale specific to UsHF due to its novel nature in the way it delivers haptic feedback. For example, this scale could include elements that help establish subjective perception of UsHF characteristics like intensity, edge definition, object accuracy, ease of use, and so forth.

8.6.3. Novel Contributions to Knowledge

At the time of starting this PhD, there was no literature to support the understanding of human factors considerations for the use and implementation of UsHF. Since embarking on this work, one publication began exploring the effect age can have on the perception of different UsHF objects (Rutten, Frier, Van den Bogaert, & Geerts, 2019), an unsurprising development given that the literature supports varying tactile ability as a function of age (e.g., Thornbury & Mistretta, 1981; Tremblay & Master, 2015; Verrillo, 1980; Wickremaratchi & Llewelyn, 2006). Despite the aforementioned research supporting tactile differences determined by age, these differences were not found in the current size discrimination tasks. However, this is still a valuable contribution to the literature as it allows future research to focus on other populational differences in UsHF interaction.

The research conducted during this PhD however, did ascertain clear, general limitations in mid-air object size discrimination, which previously had no associated research. These findings suggest limitations in size differences that people can determine, which appears to be approximately 21mm in difference (Section 4.2). Thus, in turn having implications for the sizes of objects that can be produced in applied settings whilst being able to make them distinguishable from one another.

This thesis has highlighted differences in the perception of UsHF intensity, a previously untouched area of investigation, establishing that UsHF intensity can have a significant impact on the perception of mid-air object sizes. The research into this facet of UsHF can have both a positive and negative impact on implementations of UsHF, both within and outside of engineering design, which have been explored in previous sections (Section 4.3, Chapter 5, 7 and Section 8.3.2). Furthermore, this research established absolute limitations in intensity detect to be approximately 30% (Section 4.2).

On a theoretical level, this work has also explored in detail, existing haptic technologies, UsHF and VR and where those technologies fit into the engineering design process, achieved not only through a review of the existing literature, but from gathering new data based on the opinions and feedback of both industrial and academic engineers. This is an important step in creating beneficial and effective implementations of any new technology, but particularly for one as novel and disparate compared to existing haptic solutions.

On a final note, this work is the most comprehensive look into human factors considerations for both UsHF perception and the application of UsHF within engineering design. The facets of this thesis offer the reader a guide to VR, haptics, UsHF, human factors of UsHF and UsHF applications on a nuanced level, offering technical knowledge, indicators of the technical limitations of UsHF and advice for future research and applications of the technology, not only specific to engineering design, but VR in general. The importance of this research cannot be understated due to the growing desire for more realistic interaction within the growing field of VR, which seeks more innovative, useable and realistic haptics solutions.

8.7. Chapter Summary

This chapter offered a comprehensive review of the research conducted during the course of this PhD whilst considering the existing literature, what the findings mean and how they should be considered during future research and applications of UsHF. A review of the initial aims and objectives was undertaken, citing how these were satisfied. Furthermore, consideration was given to the limitations of this research, recommendations for future implementations of UsHF and future research in the field, and the novel contributions of this work were explored.

Chapter 9: Conclusions

This research sought to investigate novel mid-air haptic feedback to support VR engineering design, an application which requires high fidelity and accurate virtual modelling. As such, this thesis has explored the human factors issues associated with perception of UsHF stimuli, both standalone, and compared to multimodal virtual and physical environments with the aim of applying knowledge gained to improve the virtual engineering design process. Furthermore, this research has investigated the acceptance and opinions of both people within industry and participants during studies in order to ascertain where VR and UsHF can be best employed within engineering and how it can be improved. In turn, findings from these studies can also be used to form new, meaningful research. The literature review established widely accepted differences in tactile ability, particularly at a populational level (e.g., age, gender and hand/fingertip size), but when embarking on this PhD, no prior work had been conducted exploring those elements or indeed the psychophysical perception of mid-air haptic stimuli. As such, this PhD sought to address the literary deficit by exploring the aforementioned elements of UsHF perception in a nuanced fashion.

In exploring the human factors concerns and psychophysical perception of UsHF stimuli, a series of testing paradigms were created in order to establish limitations in UsHF object size perception, UsHF absolute tactile thresholds, individual differences in perception and how those elements are transferred to multimodal tasks using UsHF as well as comparing these tasks using physical object analogues. Whilst populational differences in UsHF tactile perception were not found during the studies conducted for this PhD, a number of salient findings were established that afford a better understanding of the perceptual issues, benefits and limitations of UsHF for multimodal engineering design applications.

Firstly, this work established limitations in perception of mid-air object size and absolute tactile thresholds. Secondly, it discovered the effect UsHF intensity can have on the psychophysical perception of mid-air object sizes. Thirdly, it identified how multimodality in the form of visual feedback can both be a compliment and detriment to perception of mid-air object size, the latter of which refers to an apparent visual dominance when both visual and haptic stimuli were given. Finally, it established how effectively UsHF can imitate physical objects and compared perception of UsHF size differences to physical analogues. While this research was conducted within the context of virtual engineering design, it should not be understated that these findings are also useful for all implementations of UsHF.

It can be concluded that UsHF poses an attractive solution for bridging the gap between virtual and real worlds, with relatively accurate rendition of virtual objects, ease of use that requires little training, portability and convenience. However, this assertion does not come without its caveats. In order to create accurate renditions of virtual objects, it is imperative that subjective intensity is normalised on an individual application basis. This will not likely be an easy task but is necessary in order to ensure accurate rendering of mid-air objects, which is particularly salient in scenarios that require a high degree of accuracy, such as engineering design.

When considering the implications this research has for applications of UsHF, it is likely that high fidelity applications of UsHF will not be possible with the technology in its current state, and instead implementations may need to be confined to situations which require simple collision or confirmational feedback in virtual environments and interfaces, for example, to signify contact with virtual objects or interaction with a gesture-based control interface. It is possible that UsHF could be applied to early engineering design phases, such as VR visualisation, particularly when presenting design ideas to stakeholders and multidisciplinary teams that would not otherwise understand CAD models. Thus, while this research has identified some of the fundamental human factors considerations of UsHF feedback, further work is needed before the benefits of this exciting technology can be fully realised within an engineering process.

References

Abdouni, A., Djaghloul, M., Thieulin, C., Vargiolu, R., Pailler-Mattei, C., & Zahouani, H. (2017). Biophysical properties of the human finger for touch comprehension: influences of ageing and gender. *Royal Society open science, 4*(8), 1-14.

Abdullah, C., Lawson, G., & Roper, T. (2017). A Virtual Environment with Haptic Feedback for Better Distance Estimation. *The 9th ACM SIGCHI Symposium on Engineering Interactive Computing Systems* (pp. 1-6). Lisbon: EICS.

Abulrub, A., Attridge, A., & Williams, M. (2011). Virtual reality in engineering education: The future of creative learning. *IEEE global engineering education conference (EDUCON)* (pp. 751-757). Amman: IEEE.

Adams, R., Klowden, D., & Hannaford, B. (2001). Virtual Training for a Manual Assembly Task. *Haptics-e*, *2*(2), 1-7.

Aggarwal, R., Moorthy, K., & Darzi, A. (2004). Laparoscopic skills training and assessment. *British Journal of Surgery, 91*, 1549-1558.

Ahlberg, G., Enochsson, L., Gallagher, A., Hedman, L., Hogman, C., McClusky, D., . . . Arvidsson, D. (2007). Proficiency-based virtual reality training significantly reduces the error rate for residents during their first 10 laparoscopic cholecystectomies. *The American Journal of Surgery, 193(6)*, 797-804.

Al-Ahmari, A., Abidi, M., Ahmad, A., & Darmoul, S. (2016). Development of a virtual manufacturing assembly simulation system. *Advances in Mechanical Engineering*, *8*(3), 1-13.

AlZhrani, G., Alotaibi, F., Azarnoush, H., Winkler-Schwartz, A., Sabbagh, A., Bajunaid, K., . . . Del Maestro, R. F. (2015). Proficiency Performance Benchmarks for Removal of Simulated Brain Tumors Using a Virtual Reality Simulator NeuroTouch. *Journal of surgical education, 72*(4), 685-696.

Augurelle, A. S., Smith, A. M., Lejeune, T., & Thonnard, J. L. (2003). Importance of cutaneous feedback in maintaining a secure grip during manipulation of hand-held objects. *Journal of Neurophysiology, 89*(2), 665-671.

Azmandian, M., Hancock, M., Benko, H., Ofek, E., & Wilson, A. (2016). Haptic Retargeting: Dynamic Repurposing of Passive Haptics for Enhanced Virtual Reality Experiences. *Proceedings of the 2016 chi conference on human factors in computing systems*, (pp. 1967-1979). San Jose, CA.

Bailey, J., & Bailenson, J. (2017). Considering virtual reality in children's lives. *Journal of Children and Media, 11*(1), 107-113.

Banakou, D., Groten, R., & Slater, M. (2013). Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proceedings of the National Academy of Sciences of the United States of America*, *110*, pp. 12846-12851.

Bassanino, M., Wu, K., Yao, J., Khosrowshahi, F., Fernando, T., & Skjærbæk, J. (2010). The impact of immersive virtual reality on visualisation for a design review in construction. *14th International Conference Information Visualisation* (pp. 585-589). IEEE.

Bastian, H. (1887). The "Muscular Sense": Its Nature and Cortical Localisation. *Brain, 10*(1), 1-89.

Berg, L., & Vance, J. (2017). Industry use of virtual reality in product design and manufacturing: A survey. *Virtual Reality, 21*(1), 1-17.

Berryman, L., Yau, J., & Hsiao, S. (2006). Representation of object size in the somatosensory system. *Journal of Neurophysiology, 96*(1), 27-39.

bHaptics. (2022). Retrieved January 25th, 2022, from www.bhaptics.com/tactsuit/tactsuit-x40

Bjork, S., & Holopainen, J. (2005). *Patterns in game design.* Boston: Charles River Media.

Bordegoni, M., & Caruso, G. (2012). Mixed reality distributed platform for collaborative design. *Virtual and Physical Prototyping, 7*(4), 243-259.

Bordegoni, M., & Cugini, U. (2008). The role of haptic technology in the development of aesthetic driven products. *Journal of Computing and Information Science in Engineering, 8*(4), 1-10.

Botden, M., Torab, F., Buznik, S., & Jakimowicz, J. (2008). The importance of haptic feedback in laparoscopic suturing training and the additive value of virtual reality simulation. *Surgical Endoscopy, 22*, 1214-1222.

Botvinick, M., & Cohen, J. (1998). Rubber hands 'feel'touch that eyes see. *Nature, 391*(6669), 756-756.

Bourdot, P., Convard, T., Picon, F., Ammi, M., Touraine, D., & Vézien, J. (2010). R–CAD integration: Multimodal immersive interaction and advanced haptic paradigms for implicit edition of CAD models. *Computer-Aided Design, 42*(5), 445-461.

Bowman, D., & McMahan, R. (2007). Virtual reality: how much immersion is enough? *Computer, 40*(7), 36-43.

Bruce, M. (1980). The relation of tactile thresholds to histology in the fingers of elderly people. *Journal of Neurology, Neurosurgery & Psychiatry*, *43*(8), 730-734.

Bruno, F., & Muzzupappa, M. (2010). Product interface design: A participatory approach based on virtual reality. *International journal of human-computer studies, 68*(5), 254-269.

Burdea, G. (1999). Haptic feedback for virtual reality. *Virtual reality and prototyping workshop, 2*, 17-29.

Burdea, G. (1999). Keynote Address: Haptic Feedback for Virtual Reality. *Proceedings of International Workshop on Virtual prototyping*, (pp. 87-96). Laval, France.

Burdea, G., Richard, P., & Coiffet, P. (1996). Multimodal virtual reality: Input-output devices, system integration, and human factors. *International Journal of Human-Computer Interaction, 8*(1), 5-24.

Burke, D., Gandevia, S., & Macefield, G. (1988). Responses to passive movement of receptors in joint, skin and muscle of the human hand. *The Journal of physiology, 402*(1), 347-361.

Burnett, G. (2001). Ubiquitous computing within cars: Designing Controls for non-visual use. *International Journal of Human-Computer Studies, 55*, 521-531.

Carter, T., Seah, S., Long, B., Drinkwater, B., & Subramanian, S. (2013). UltraHaptics: Multi-Point Mid-Air Haptic Feedback for Touch. *Proceedings of the 26th annual ACM symposium on User interface software and technology*, (pp. 505-514).

Cesanek, E., & Domini, F. (2018). Transfer of adaptation reveals shared mechanism in grasping and manual estimation. *Neuropsychologia, 117*, 271-277.

Choi, P., Oskouian, R., & Tubbs, R. (2018). Telesurgery: past, present, and future. *Cureus, 10*(5), 1-5.

Chun Tie, Y., Birks, M., & Francis, K. (2019). Grounded theory research: A design framework for novice researchers. *SAGE Open Medicine, 7*, 1-8.

Cocchini, G., Galligan, T., Mora, L., & Kuhn, G. (2018). The magic hand: Plasticity of mental hand representation. *Quarterly Journal of Experimental Pyschology*, 1-11.

Cohen, A., & Chen, E. (1999). Six degree-of-freedom haptic system as a desktop virtual prototyping interface. *ASME International Mechanical Engineering Congress and Exposition* (pp. 1-10). American Society of Mechanical Engineers.

Cole, J. (1995). *Pride and a Daily Marathon.* MIT Press.

Cole, J., & Paillard, J. (1995). Living without touch and peripheral information about body position and movement: Studies with deafferented subjects. In J.

Bermudez, A. Marcel, & N. Eilan, *The body and the self* (pp. 245-267). Cambridge, MA: MIT Press.

Culbertson, H., Schorr, S., & Okamura, A. (2018). Haptics: The present and future of artificial touch sensations. *Annual Review of Control, Robotics, and Autonomous Systems*, 12.1-12.25.

Dalecki, D., Child, S., Raeman, C., & Carstensen, E. (1995). Tactile perception of ultrasound. *The Journal of the Acoustical Society of America, 97*, 3165.

Davis, F. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. (319-340, Ed.) *MIS Quarterly*.

Dillon, Y. K., Haynes, J., & Henneberg, M. (2001). The relationship of the number of Meissner's corpuscles to dermatoglyphic characters and finger size. *Journal of Anatomy, 199*, 577-584.

Dillon, Y., Haynes, J., & Henneberg, M. (2001). The relationship of the number of Meissner’s corpuscles to dermatoglyphic characters and finger size. *Journal of Anatom, 199*, 577-584.

Fairhurst, M., Travers, E., Hayward, V., & Deroy, O. (2018). Confidence is higher in touch than in vision in cases of perceptual ambiguity. *Scientific Reports, 8*(1), 15604-15609.

Ferrise, F., Bordegoni, M., & Cugini, U. (2013). Interactive virtual prototypes for testing the interaction with new products. *Computer-Aided Design and Applications, 10*(3), 515-525.

Ferrise, F., Furtado, G., Graziosi, S., & Bordegoni, M. (2013). Digitalizing and capturing haptic feedback in virtual prototypes for user experience design. *18th International Conference on Digital Signal Processing (DSP)* (pp. 1-7). IEEE.

Field, A. (2014). *Discovering Statistics Using IBM SPSS Statistics* (4th ed.). London: SAGE Publications Ltd.

Flanagan, J., Bowman, M., & Johansson, R. (2006). Control Strategies in Object Manipulation Tasks. *Current Opinion in Neurobiology, 16*, 650-659.

Fortes, B., Balsalobre, L., Weber, R., Stamm, R., Stamm, A, . . . Coronel, N. (2016). Endoscopic sinus surgery dissection courses using a real simulator: the benefits of this training. *Brazilian Journal of Otorhinolaryngology, 82*, 26-32.

Galambos, P. (2021). Vibrotactile Feedback for Haptics and Telemanipulation: Survey, Concept and Experiment. *Acta Polytechnica Hungarica, 9*(1), 41-65.

Gallace, A., & Spence, C. (2014). *In Touch with the Future*. Oxford: Oxford University Press.

Gallace, A., Tan, H., & Spence, C. (2007). The body surface as a communication system: The state of the art after 50 years. *Presence: Teleoperators and Virtual Environments, 16*(6), 655-676.

Georgiou, O., Jeffrey, C., Chen, Z., Tong, B., Chan, S., Yang, B., . . . Carter, T. (2018). Touchless Haptic Feedback for VR Rhythm Games. *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, (pp. 553-554).

Giachritsis, C., Wright, R., & Wing, A. (2010). The contribution of proprioceptive and cutaneous cues in weight perception: early evidence for maximum-likelihood integration. *nternational Conference on Human Haptic Sensing and Touch Enabled Computer Applications* (pp. 11-16). Berlin: Springer.

Gibson, I., Brown, D., Cobb, S., & Eastgate, R. (1993). Virtual Reality and Rapid Prototyping: Conflicting or Complimentary? *International Solid Freeform Fabrication Symposium*, (pp. 113-120).

Gibson, J. (1933). Adaptation, after-effect and contrast in the perception of curved lines. *Journal of Experimental Psychology, 16*(1).

Goldreich, D., & Kanics, I. (2006). Performance of blind and sighted humans on a tactile grating detection task. *Perception & Psychophysics, 68*(8), 1363-1371.

Gupta, S., Morris, D., Patel, S., & Tan, D. (2013). AirWave: Non-Contact Haptic Feedback Using Air Vortex Rings. *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing*, (pp. 419-428). Zurich.

Ha, S., Kim, L., Park, S., Jun, C., & Rho, H. (2009). Virtual prototyping enhanced by a haptic interface. *CIRP Annals, 58*(1), 135-138.

Haber, R., & Levin, C. (2001). The independence of size perception and distance perception. *Perception & psychophysics, 63*(7), 1140-1152.

Haggard, P., & Jundi, S. (2009). Rubber hand illusions and size–weight illusions: self-representation modulates representation of external objects. *Perception, 38*(12), 1796-1803.

Haike, Y., & Shahin, T. (2011). *Engineering Design Process* (Second Edition ed.). Stamford, USA: Cengage Learning.

Halbleib, H. (2004). Requirements Management. *Information Systems Management, 21*(1), 8-14.

Hanson, J., Whitaker, D., & Heron, J. (2009). Preferential processing of tactile events under conditions of divided attention: Effects of divided attention on reaction time. *Neuroreport, 20*(15), 1-7.

HaptX. (2022). Retrieved January 25th, 2022, from www.haptx.com

Harris, J., Miniussi, C., Harris, I., & Diamond, M. (2002). Transient storage of a tactile memory trace in primary somatosensory cortex. *Journal of Neuroscience, 22*(19), 8720-8725.

Hayward, V., Astley, O., Cruz-Hernandez, M., Grant, D., & Robles-De-La-Torre, G. (2004). Haptic Interfaces and Devices. *Sensor Review, 24*(1), 16-29.

Hecht, D., & Reiner, M. (2009). Sensory dominance in combinations of audio, visual and haptic stimuli. *Experimental Brain Research, 193*, 307–314.

Heller, M. (1992). Haptic dominance in form perception: vision versus proprioception. *Perception, 21*(5), 655-660.

Hinchet, R., Vechev, V., Shea, H., & Hilliges, O. (2018). DextrES: Wearable Haptic Feedback for Grasping in VR via a Thin Form-Factor Electrostatic Brake.

Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology, (pp. 901-912). Berlin, Germany.

Hodzic, A., Veit, R., Karim, A., Erb, M., & Godde, B. (2004). Improvement and decline in tactile discrimination behavior after cortical plasticity induced by passive tactile coactivation. *Journal of Neuroscience, 24*(2), 442-446.

Hollins, M., & Risner, S. (2000). Evidence for the duplex theory of tactile texture perception. *Perception & Psychophysics, 62*, 695-701.

Hong, Y., Bruniaux, P., Zeng, X., Liu, K., Chen, Y., & Dong, M. (2017). Virtual reality-based collaborative design method for designing customized garment for disabled people with scoliosis. *International Journal of Clothing Science and Technology, 29*(2), 226-237.

Hoshi, T., Takahashi, M., Iwamoto, T., & Shinoda, H. (2010). Noncontact Tactile Display Based on Radiation Pressure of Airborne Ultrasound. *IEEE Transactions on Haptics, 3*(3), 155-165.

Iwata, H., Yano, H., Nakaizumi, F., & Kawamura, R. (2001). Project FEELEX: Adding Haptic Surface to Graphics. *Proceedings of the 28th annual conference on Computer graphics and interactive techniques*, (pp. 469-476).

Jaijongrak, V., Kumazawa, I., & Thiemjarus, S. (2011). A haptic and auditory assistive user interface: Helping the blinds on their computer operations. *IEEE International Conference on Rehabilitation Robotics* (pp. 1-6). IEEE.

Jenmalm, P., & Johansson, R. (1997). Visual and Somatosensory Information About Object Shape Control Manipulative Fingertip Forces. *Journal of Neuroscience, 17*, 4486-4499.

Johansson, R., & Flanagan, J. (2009). Coding and use of tactile signals from the fingertips in object manipulation tasks. *Nature Reviews Neuroscience, 10*, 345-359.

Johansson, R., Westling, G., Backstrom, A., & Flanagan, J. (2001). Eye-hand coordination in object manipulation. *The Journal of Neuroscience, 21*, 6917-6932.

Jung, S., Bruder, G., & Wisniewski, P. (2018). Over My Hand: Using a Personalized Hand in VR to Improve Object Size Estimation, Body Ownership, and Presence. *Proceedings of the Symposium on Spatial User Interaction* (pp. 60-68). Berlin: ACM.

Just, M., Stirling, D., Ros, M., Naghdy, F., Donley, J., & Stapley, P. (2016). The Effects of Reintroducing Haptic Feedback to Virtual-Reality Systems on Movement Profiles When Reaching to Virtual Targets. *11th International Conference on Disability, Virtual Reality and Associated Technologies (ICDVRAT 2016),* (pp. 319-322).

Kalisch, T., Ragert, P., Schwenkreis, P., Dinse, H., & Tegenthoff, M. (2009). Impaired tactile acuity in old age is accompanied by enlarged hand representations in somatosensory cortex. *Cerebral Cortex, 19*(7), 1530-1538.

Kenyon, R., Phenany, M., Sandin, D., & Defanti, T. (2007). Accommodation and size-constancy of virtual objects. *Annals of Biomedical Engineering, 36*(2), 342-348.

Kern, T. (2009). *Engineering Haptic Devices: A Beginner's Guide.* Springer Publishing Company, Incorporated.

Kim, E., & Schneider, O. (2020). Defining Haptic Experience: Foundations for Understanding, Communicating, and Evaluating HX. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, (pp. 1-13). Honolulu.

Kim, M., Ryu, J., Son, J., & Han, J. (2022). Virtual object sizes for efficient and convenient mid-airmanipulation. *The Visual Computer, 38*, 3463-3474.

Kohtala, S., Erichsen, J., Sjoman, H., & Steinert, M. (2018). Augmenting Physical Prototype Activities in Early-Stage Product Development. *Proceedings of NordDesign 2018*, (pp. 1-15). Linkoping, Sweden.

Koizumi, N., & Sano, A. (2020). Optical System to Display Mid-Air Images on a Glossy Plane and Remove Ground Images. *Optics Express, 28*(18), 26750-26763.

Kovar, J., Mouralova, K., Ksica, F., Kroupa, J., Andrs, O., & Hadas, Z. (2016). Virtual Reality in Context of Industry 4.0 Proposed Projects at Brno University of Technology. *17th International Conference on Mechatronics* (pp. 1-7). IEEE.

Kremer, K. (1998). A concept for virtual reality tools for design reviews. *Proceedings Visualization'98* (pp. 205-210). IEEE.

Kristensen, S., Fracasso, A., Dumoulin, S., Almeida, J., & Harvey, B. (2021). Size constancy affects the perception and parietal neural representation of object size. *Neuroimage, 232*(117909), 1-11.

Kumar, V. S. (2006). Effective Requirements Management. *PMI Global Congress.* Madrid: EMEA.

Kusumoto, N., Sohmura, T., Yamada, S., Wakabayashi, K., Nakamura, T., & Yatani, H. (2006). Application of Virtual Reality Force Feedback Haptic Device for Oral Implant Surgery. *Clinical Oral Implants Research*, *17*(6), 705-713.

Large, D., Harrington, K., Burnett, G., & Georgiou, O. (2019). Feel the noise: Mid-air ultrasound haptics as a novel human-vehicle interaction paradigm. *Applied Ergonomics, 81*, 1-10.

Larsson, T., & Torlind, P. (2001). Using VR in the mechanical design process. 1-28.

Lawson, G., Salanitri, D., & Waterfield, B. (2015). VR processes in the automotive industry. *International Conference on Human-Computer Interaction* (pp. 208-217). Springer.

Linkenauger, S., Ramenzoni, V., & Proffitt, D. (2010). Illusory shrinkage and growth: Body-based rescaling affects the perception of size. *Psychological Science, 21*(9), 1318-1325.

Liu, X., Dodds, G., McCartney, J., & Hinds, B. (2004). Virtual DesignWorks—designing 3D CAD models via haptic interaction. *Computer-Aided Design, 36*(12), 1129-1140.

Loftin, R., & Kenney, P. (1995). Training the Hubble Space Telescope Flight Team. *IEEE Computer Graphics and Applications*, *15*(5), 31-37.

Long, B., Seah, S., Carter, T., & Subramanian, S. (2014). Rendering Volumetric Haptic Shapes in Mid-Air using Ultrasound. *ACM Transactions on Graphics, 33*(6), 1-10.

Lucaites, K., Venkatakrishnan, R., Venkatakrishnan, R., Bhargava, A., & Pagano, C. (2020). Predictability and Variability of a Dynamic Environment Impact Affordance. *Ecological Psychology, 32*(2-3), 95-114.

Mahdjoub, M., Monticolo, D., Gomes, S., & Sagot, J. (2010). A collaborative design for usability approach supported by virtual reality and a multi-agent system embedded in a PLM environment. *Computer-Aided Design, 42*(5), 402-413.

Mahoney, D. (2000). Hands-on modeling. *Computer Graphics World, 23*(3), 13-14.

Makin, L., Barnaby, G., & Roudaut, A. (2019). Tactile and kinesthetic feedbacks improve distance perception in virtual reality. *Proceedings of the 31st Conference on l'Interaction Homme-Machine*, (pp. 1-9). Grenoble.

Mami, F., Reveret, J., Fallaha, S., & Margini, M. (2017). Evaluating Eco-Efficiency of 3D Printing in the Aeronautic Industry. *Journal of Industrial Ecology*, 1-12.

Martinez, J., Griffiths, D., Biscione, V., Georgiou, O., & Carter, T. (2018). Touchless Haptic Feedback for Supernatural VR Experiences . *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (pp. 629-630). IEEE.

Miyaoka, T., Mano, T., & Ohka, M. (1999). Mechanisms of fine-surface-texture discrimination in human tactile sensation. *The journal of the acoustical society of America, 105*(4), 2485-2492.

Mujber, T., Szecsi, T., & Hashmi, M. (2004). Virtual Reality Applications in Manufacturing Process Simulation. *Journal of Materials Processing Technology*, 1834-1838.

Mullenbach, J., Johnson, D., Colgate, J. E., & Peshkin, M. A. (2012). ActivePaD Surface Haptic Device. *2012 IEEE Haptics Symposium (HAPTICS)* (pp. 407-414). Vancouver: IEEE.

Naef, M., & Payne, J. (2007). Autoeval mkII-interaction design for a VR design review system. *2007 IEEE Symposium on 3D User Interfaces* (pp. 45-48). Charlotte: IEEE.

Nilsson, T., Roper, T., Shaw, E., Lawson, G., Cobb, S., Meng-Ko, H., . . . Khan, J. (2019). Multisensory virtual environment for fire evacuation training. *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems* (pp. 1-4). ACM.

Nizam, S., Abidin, R., Hashim, N., Lam, M., Arshad, H., & Majid, N. (2018). A review of multimodal interaction technique in augmented reality environment. *International Journal on Advanced Science Engineering and Information Technology, 8*(4-2), 1460-1469.

Nowak, D. A., Glasauer, S., & Hermsdörfer, J. (2004). How Predictive is Grip Force Control in the Complete Absence of Somatosensory Feedback? *Brain, 127*(1), 182-192.

Nowak, D., Hermsdörfer, J., Glasauer, S., Philipp, J., Meyer, L., & Mai, N. (2001). The effects of digital anaesthesia on predictive grip force adjustments during vertical movements of a grasped object. *European Journal of Neuroscience, 14*(4), 756-762.

O’Shea, H., & Redmond, S. (2021). A Review of the Neurobiomechanical Processes Underlying Secure Gripping in Object Manipulation. *Neuroscience & Biobehavioral Reviews, 123*, 286-300.

Ogawa, N., Narumi, T., & Hirose, M. (2017). Distortion in Perceived Size and Body-based Scaling in Virtual Environments. *Proceedings of the 8th Augmented Human International Conference,* (pp. 1-5).

Panait, L., Akkary, E., Bell, R., Roberts, K., Dudrick, S., & Duffy, A. (2009). The role of haptic feedback in laparoscopic simulation training. *Journal of Surgical Research, 156*(2), 312-316.

Paré, M., & Dugas, C. (1999). Developmental Changes in Prehension During Childhood. *Experimental Brain Research, 125*(3), 239-247.

Park, J., Han, I., & Lee, W. (2019). Effect of Haptic Feedback on the Perceived Size of a Virtual Object. *IEEE Access, 7,* 83673-83681.

Patel, R., & Patel, B. (2012). Virtual reality surgical simulation in training. *Expert Review of Anticancer Therapy, 12(4),* 417-420.

Peters, R., Hackeman, E., & Goldreich, D. (2009). Diminutive Digits Discern Delicate Details: Fingertip Size and the Sex Difference in Tactile Spatial Acuity. *The Journal of Neuroscience, 29*(50), 15756-15761.

Powers, M. (2007). Surgical Scissors Extension Adds the 7th Axis of Force Feedback to the Freedom 6S. *Medicine Meets Virtual Reality*, 361-366.

Purves, D., Augustine, G. J., Fitzpatrick, D., Katz, L. C., LaMantia, A. S., O McNamara, J., & Williams, S. M. (2001). Mechanoreceptors Specialized to Receive Tactile Information. In *Neuroscience.* Sunderland, MA: Sinauer Associates.

Rakkolainen, I., Freeman, E., Sand, A., Raisamo, R., & Brewster, S. (2020). A survey of mid-air ultrasound haptics and its applications. *IEEE Transactions on Haptics, 14*(1), 1-18.

Renner, R. V. (2014). The perception of egocentric distances in Virtual Environments. *ACM Computing Surveys*, 1-38.

Riva, G., Mantovani, F., Capideville, C., Preziosa, A., Morganti, F., Villani, D., . . . Alcaniz, M. (2007). Affective Interactions Using Virtual Reality: The Link between Presence and Emotions. *CyberPsychology & Behavior, 10*(1), 45-56.

Robles-De-La-Torre, G. (2006). The Importance of the Sense of Touch in Virtual and Real Environments. *IEEE Multimedia, 13*(3), 24-30.

Rohde, M., Di Luca, M., & Ernst, M. (2011). The rubber hand illusion: feeling of ownership and proprioceptive drift do not go hand in hand. *PloS One, 6*(6), 1-9.

Rosenbaum, D., Chapman, K., Weigelt, M., Weiss, D., & van der Wel, R. (2012). Cognition, action, and object manipulation. *Psychological Bulletin, 138*(5), 924-946.

Rümelin, S., Gabler, T., & Bellenbaum, J. (2017). Clicks are in the air: How to support the interaction with floating objects through ultrasonic feedback. *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, (pp. 103-108).

Rutten, I., Frier, W., Van den Bogaert, L., & Geerts, D. (2019). Invisible touch: How identifiable are mid-air haptic shapes? *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*, (pp. 1-6). Glasgow.

Ryge, A., Thomsen, L., Berthelsen, T., Hvass, J., Koreska, L., Vollmers, C., . . . Serafin, S. (2017). Effect on high versus low fidelity haptic feedback in a virtual reality baseball simulation. *IEEE Virtual Reality (VR)* (pp. 365-366). Los Angeles: IEEE.

Scott, D., Bergen, P., Rege, R., Laycock, R., Tesfay, S., Valentine, R., . . . Jones, D. (2000). Laparoscopic training on bench models: better and more cost effective than operating room experience? *Journal of The American College of Surgeons, 191(3),* 272-283.

Seth, A., Su, H., & Vance, J. (2006). SHARP: A system for haptic assembly and realistic prototyping. *International Design Engineering Technical Conferences* *and Computers and Information in Engineering Conference*, *42578*, pp. 905-912.

Seth, A., Vance, J., & Oliver, J. (2011). Virtual Reality for Assembly Methods in Prototyping: A Review. *Virtual Reality*, *15*(1), 5-20.

Seymour, N., Gallagher, A., Roman, S., O'Brien, M., Bansal, V., Andersen, D., & Satava, R. (2002). Virtual reality training improves operating room performance. *Annals of Surgery, 236(4)*, 458-464.

Shakeri, G., Williamson, J. H., & Brewster, S. (2018). May the force be with you: Ultrasound haptic feedback for mid-air gesture interaction in cars. *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, (pp. 1-10).

Sherrington, C. (1906). *The Integrative Action.* New Haven: Yale University Press.

Sjostrom, C. (2001). Designing haptic computer interfaces for blind people. *Proceedings of the Sixth International Symposium on Signal Processing and its Applications,* (pp. 68-71).

Slater, M., & Wilbur, S. (1997). A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments. *Presence: Teleoperators & Virtual Environments, 6*(6), 603-616.

Son, B., & Park, J. (2018). Haptic Feedback to the Palm and Fingers for Improved Tactile Perception of Large Objects. *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, (pp. 757-763). Berlin, Germany.

Spagnoletti, G., Meli, L., Baldi, T. L., Gioioso, G., Pacchierotti, C., & Prattichizzo, D. (2018). Rendering of Pressure and Textures Using Wearable Haptics in Immersive VR Environments. *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (pp. 681-692). Reutlingen: IEEE.

Spence, C. (2016). Making sense of touch: a multisensory approach to the perception of objects. In E. Pye, *The Power of Touch: Handling Objects in Museum and Heritage Contexts* (pp. 45-61). Routledge.

Sreelakshmi, M., & Subash, T. (2017). Haptic Technology: A Comprehensive Review on its Applications and Future Prospects. *Materials Today: Proceedings 4.2*, (pp. 4182-4187).

Stillman, B. (2002). Making Sense of Proprioception: The Meaning of Proprioception, Kinaesthesia and Related Terms. *Physiotherapy, 88*(11), 667-679.

Stone, K., & Gonzalez, C. (2015). The contributions of vision and haptics to reaching and grasping. *Frontiers in Psychology, 6*, 1-18.

Strom, P., Hedman, L., Sarna, L., Kjellin, A., Wredmark, T., & Fellander-Tsai, L. (2006). Early exposure to haptic feedback enhances performance in surgical simulator training: a prospective randomized crossover study in surgical residents. *Surgical Endoscopy, 20*, 1383-1388.

Stuchlikova, L., Kosa, A., Benko, P., & Juhasz, P. (2017). Virtual Reality Vs. Reality in Engineering Education. *15th International Conference on Emerging eLearning Technologies and Applications (ICETA)*, (pp. 1-6).

Suzuki, Y., & Kobayashi, M. (2005). Air Jet Driven Force Feedback in Virtual Reality. *Computer Graphics and Applications*, 44-47.

Tanner, S. (1993). The Use of Virtual Reality at Boeing's Huntsville Laboratories. *Proceedings of IEEE Virtual Reality Annual International Symposium* (pp. 14-19). IEEE.

Thornbury, J., & Mistretta, C. (1981). Tactile sensitivity as a function of age. *Journal of Gerontology*(36), 34-39.

Tremblay, F., & Master, S. (2015). Touch in aging. *10*(2), 9935.

Tuthill, J. (2018). Proprioception. *Biology, 28*(5), R194-R203.

Verrillo, R. T. (1980). Age Related Changes in the Sensitivity to Vibration. *Journal of Gerontology, 35*(2), 185-193.

Vogelsang, K., Steinhüser, M., & Hoppe, U. (2013). A qualitative approach to examine technology acceptance. *Thirty Fourth International Conference on Information Systems*, (pp. 1-16). Milan.

Walsh, K., & Pawlowski, S. (2002). Virtual reality: a technology in need of IS research. *Association for Information Systems, 8*(1), 297-314.

Wastiels, L., Schifferstein, H., Wouters, I., & Heylighen, A. (2013). Touching materials visually: About the dominance of vision in building material assessment. *International Journal of Design, 7*(2), 31-41.

Wellman, P. S., Peine, W. J., Favalora, G., & Howe, R. D. (1998). Mechanical Design and Control of a High-Bandwidth Shape Memory Alloy Tactile Display. *Experimental robotics V*, 56-66.

White, P. (2012). The experience of force: the role of haptic experience of forces in visual perception of object motion and interactions, mental simulation, and motion-related judgments. *Psychological Bulletin, 138*(4), 589-615.

Wickremaratchi, M., & Llewelyn, J. (2006). Effects of ageing on touch. *Postgraduate Medical Journal, 82*(967), 301-304.

Wilson, J. (2005). Methods in the understanding of human factors. In J. Wilson, & S. Sharples, *Evaluation of Human Work* (pp. 1-31). Taylor & Francis.

Wing, A., & Wimperis, A. (2008). Impaired Haptic Size Perception Following Cortical Stroke: A Case Study. *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications* (pp. 283-288). Berlin: Springer.

Wolfartsberger, J. (2019). Analyzing the potential of virtual reality for engineering design review. *Automation in Construction, 104,* 27-37.

Wolfartsberger, J., Zenisek, J., Sievi, C., & Silmbroth, M. (2017). A virtual reality supported 3D environment for engineering design review. *23rd International Conference on Virtual System & Multimedia* (pp. 1-8). IEEE.

Wuillemin, D., Van Doorn, G., Richardson, B., & Symmons, M. (2005). Haptic and visual size judgements in virtual and real environments. *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 86-89). IEEE.

Young, R. (2003). Evolution of the Human Hand: The Role of Throwing and Cubbing. *Journal of Anatomy, 202*(1), 165-174.

Zhang, Q., Yang, X., & Robert, L. (2020). Expectations and trust in automated vehicles. *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (pp. 1-9). Honolulu: CHI.

Zheng, J., Chan, K., & Gibson, I. (1998). Virtual reality. *IEEE Potentials, 17*(2), 20-23.

Appendix A: Supplementary materials used during Study 1

1: Brief presented to participants prior to taking part – Study 1

The University of
Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

Participant Brief

For this investigation we are interested in subjective differences in the use of Ultrasound Haptic Feedback (UHF). UHF is a technology that uses ultrasound to create 'haptic' or touch feedback in mid-air, without physical contact with a surface. Of particular interest is individual ability to discriminate the difference between different size objects that are projected in mid-air using UHF.

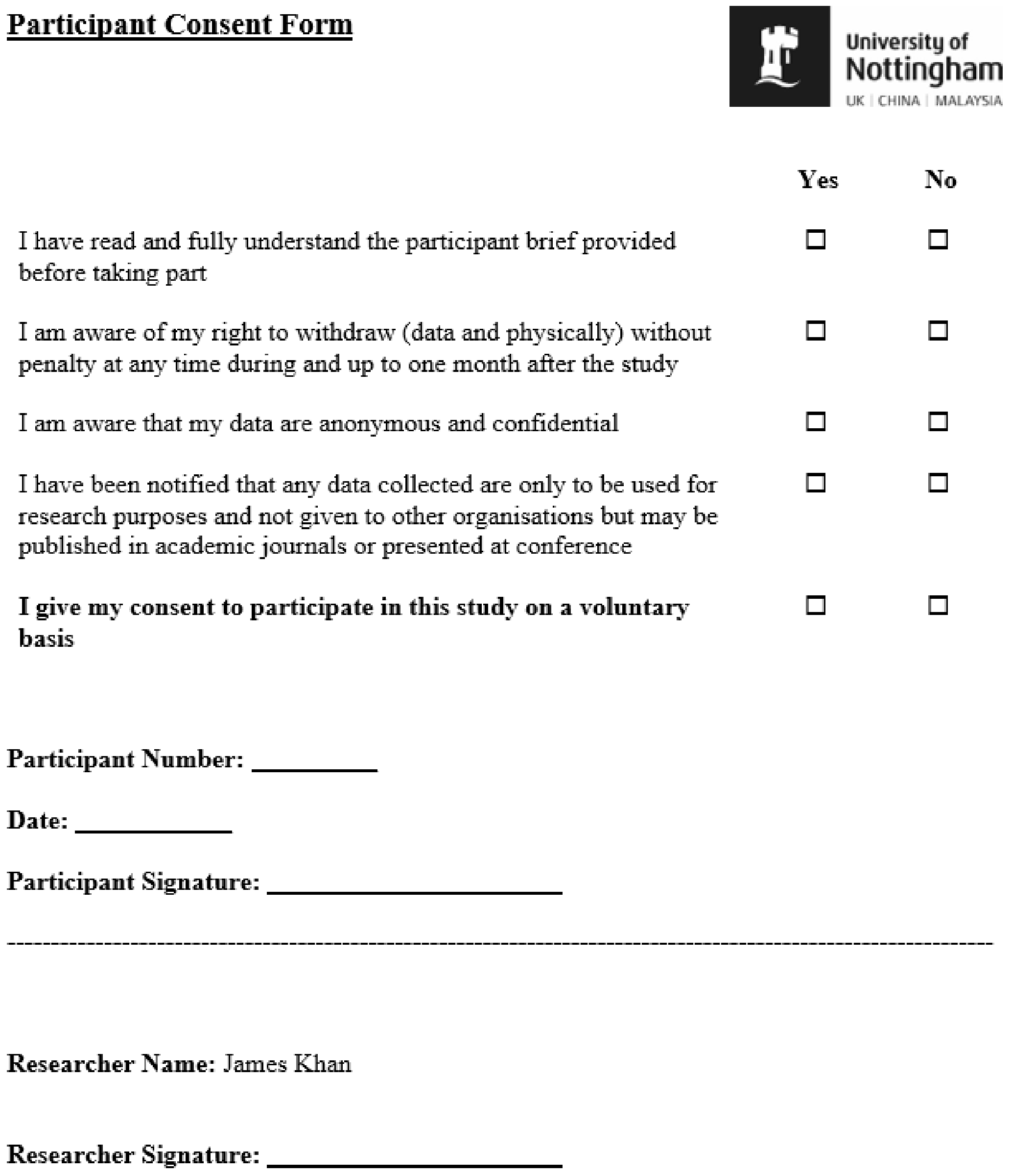
Firstly, if you agree to take part, you will be asked to sign the provided consent form and provide some details about yourself that will be kept confidential and anonymous. Before starting we need to take measurements of your dominant hand, specifically the index finger tip. Headphones playing white noise will need to be worn in order to mask any sounds the device makes. You will then take part in a short practice trial similar to the main task, during which you will not be scored on your performance. The practice allows you to acclimatise yourself with the sensation of UHF. Once completed, the main task will start. During the primary task, you will be presented with circles in pairs (one circle projected at a time), however, the two circles will differ in size. Using **ONLY** your dominant hand, your task is to discern which object is larger **(A or B)** and write down your answer on the sheet provided. You may feel the shape in any way you desire. You will have a maximum of 30 seconds to feel each shape.

Your data will be reported as part of a set and individuals will not be recognisable. The data will also remain stored in a locked computer data file accessible only by the researcher and project supervisor. These data will only be used for research purposes for a PhD project in conjunction with an industry partner.

You are able to withdraw at any point without penalty. If you wish to withdraw, please tell the experimenter. After withdrawal, your data will be removed from the study and destroyed. You have up to one month after taking part to request the removal of your data should you wish to do so. You can do this by contacting the researcher, via email – James.Khan@nottingham.ac.uk or the project supervisor, Glyn.Lawson@nottingham.ac.uk

If you have any further questions or complaints regarding ethics, please contact the Faculty of Engineering ethics committee – Robert.Houghton@nottingham.ac.uk

2: Participant consent form to be signed prior to taking part – Study 1



Participant Consent Form

University of Nottingham
UK | CHINA | MALAYSIA

	Yes	No
I have read and fully understand the participant brief provided before taking part	☐	☐
I am aware of my right to withdraw (data and physically) without penalty at any time during and up to one month after the study	☐	☐
I am aware that my data are anonymous and confidential	☐	☐
I have been notified that any data collected are only to be used for research purposes and not given to other organisations but may be published in academic journals or presented at conference	☐	☐
I give my consent to participate in this study on a voluntary basis	☐	☐

Participant Number: __________

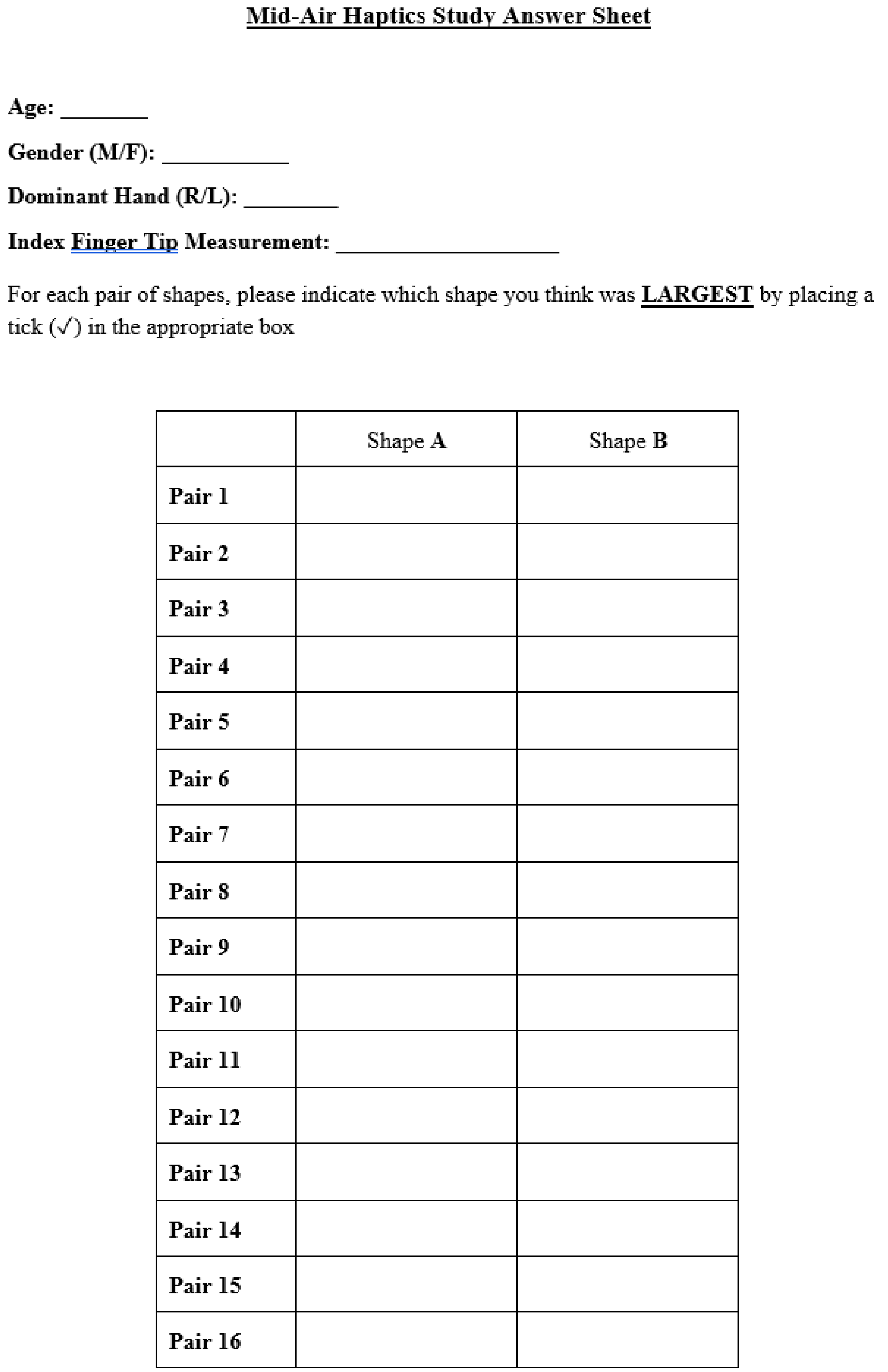
Date: ____________

Participant Signature: ______________________

Researcher Name: James Khan

Researcher Signature: ______________________

3: Participant response form used to record answers (does not include all answer cells) – Study 1



Mid-Air Haptics Study Answer Sheet

Age: ________

Gender (M/F): ___________

Dominant Hand (R/L): ________

Index Finger Tip Measurement: ____________________

For each pair of shapes, please indicate which shape you think was **LARGEST** by placing a tick (✓) in the appropriate box

	Shape **A**	Shape **B**
Pair 1		
Pair 2		
Pair 3		
Pair 4		
Pair 5		
Pair 6		
Pair 7		
Pair 8		
Pair 9		
Pair 10		
Pair 11		
Pair 12		
Pair 13		
Pair 14		
Pair 15		
Pair 16		

4: Debrief given to participants after taking part – Study 1

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

Participant Debrief

Thank you for participating in this study. Ultrasound Haptic Feedback (UHF) if a relatively new technology with many potential applications. We are interested in the use of UHF within Virtual Reality (VR) systems used for engineering design. As such, it is important to establish whether users can accurately distinguish different shapes and sizes. Furthermore, it is important that we understand whether this ability is affected by any individual traits, such as age, gender or hand size. Understanding this allows us to understand whether the intended use for UHF is possible at a basic level.

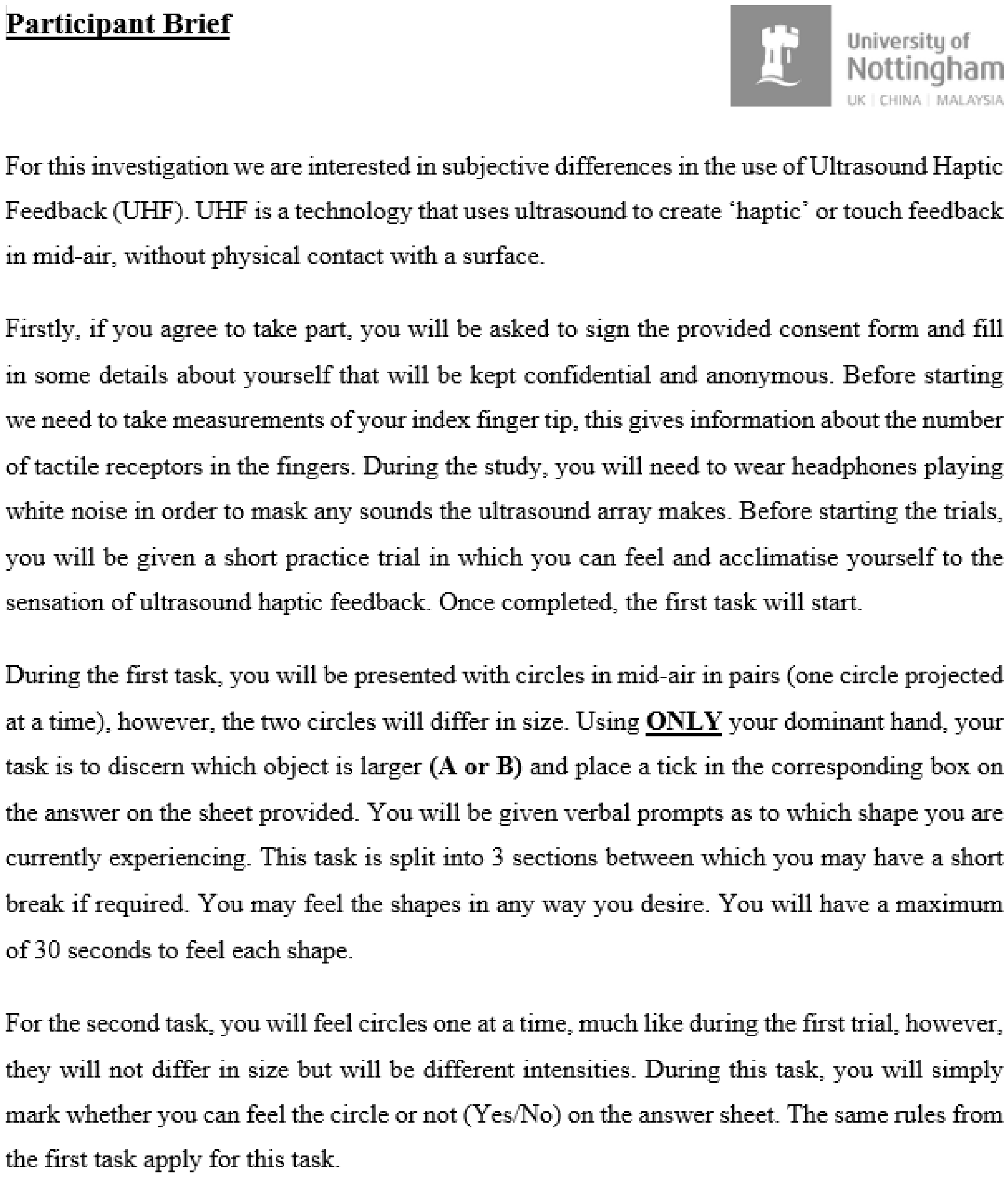
During the trials you were presented with pairs of circles one after another, after which you rated which shape was larger. The size difference between the pairs of circles will have become harder to discriminate between as you progressed through the trial. This was an important element in order to understand the limit of individual's tactile acuity. The data gathered during this experiment will allow researchers to further understand the potential applications and limitations of mid-air haptics as a control and feedback device.

If you have any questions about the investigation, would like to see the results or would like to withdraw your data, please do not hesitate to contact the researcher via email at James.Khan@nottingham.ac.uk or the project supervisor, Glyn.Lawson@nottingham.ac.uk

If you have any further questions or complaints regarding ethics, please contact the Faculty of Engineering ethics committee - Robert.Houghton@nottingham.ac.uk

Appendix B: Supplementary materials used during Study 2

1: Study brief administered to participants before taking part – Study 2



Participant Brief

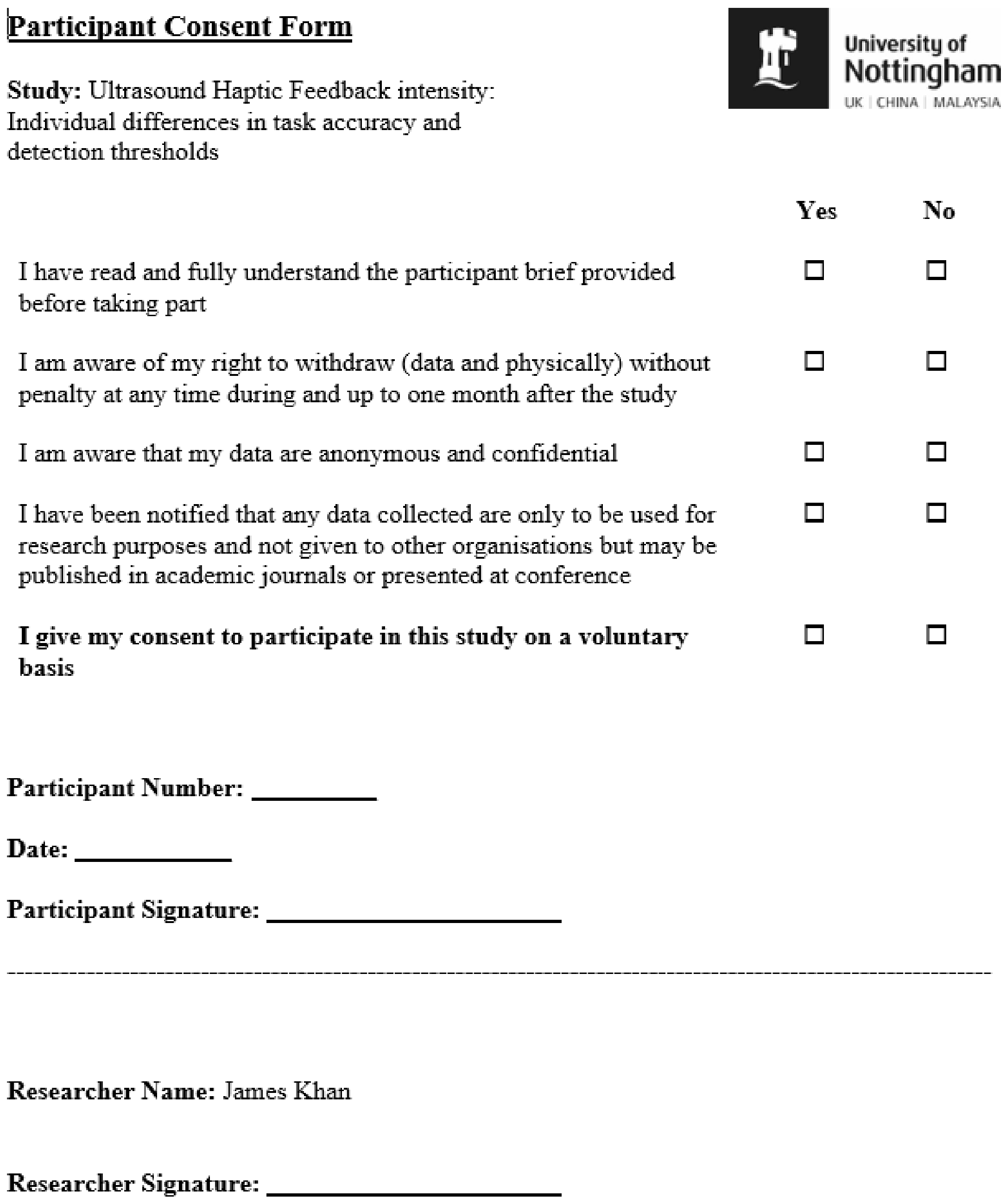
For this investigation we are interested in subjective differences in the use of Ultrasound Haptic Feedback (UHF). UHF is a technology that uses ultrasound to create ‘haptic’ or touch feedback in mid-air, without physical contact with a surface.

Firstly, if you agree to take part, you will be asked to sign the provided consent form and fill in some details about yourself that will be kept confidential and anonymous. Before starting we need to take measurements of your index finger tip, this gives information about the number of tactile receptors in the fingers. During the study, you will need to wear headphones playing white noise in order to mask any sounds the ultrasound array makes. Before starting the trials, you will be given a short practice trial in which you can feel and acclimatise yourself to the sensation of ultrasound haptic feedback. Once completed, the first task will start.

During the first task, you will be presented with circles in mid-air in pairs (one circle projected at a time), however, the two circles will differ in size. Using **ONLY** your dominant hand, your task is to discern which object is larger **(A or B)** and place a tick in the corresponding box on the answer on the sheet provided. You will be given verbal prompts as to which shape you are currently experiencing. This task is split into 3 sections between which you may have a short break if required. You may feel the shapes in any way you desire. You will have a maximum of 30 seconds to feel each shape.

For the second task, you will feel circles one at a time, much like during the first trial, however, they will not differ in size but will be different intensities. During this task, you will simply mark whether you can feel the circle or not (Yes/No) on the answer sheet. The same rules from the first task apply for this task.

2: Consent form administered to participants before taking part – Study 2



Participant Consent Form

Study: Ultrasound Haptic Feedback intensity:
Individual differences in task accuracy and
detection thresholds

	Yes	No
I have read and fully understand the participant brief provided before taking part	☐	☐
I am aware of my right to withdraw (data and physically) without penalty at any time during and up to one month after the study	☐	☐
I am aware that my data are anonymous and confidential	☐	☐
I have been notified that any data collected are only to be used for research purposes and not given to other organisations but may be published in academic journals or presented at conference	☐	☐
I give my consent to participate in this study on a voluntary basis	☐	☐

Participant Number: ____________

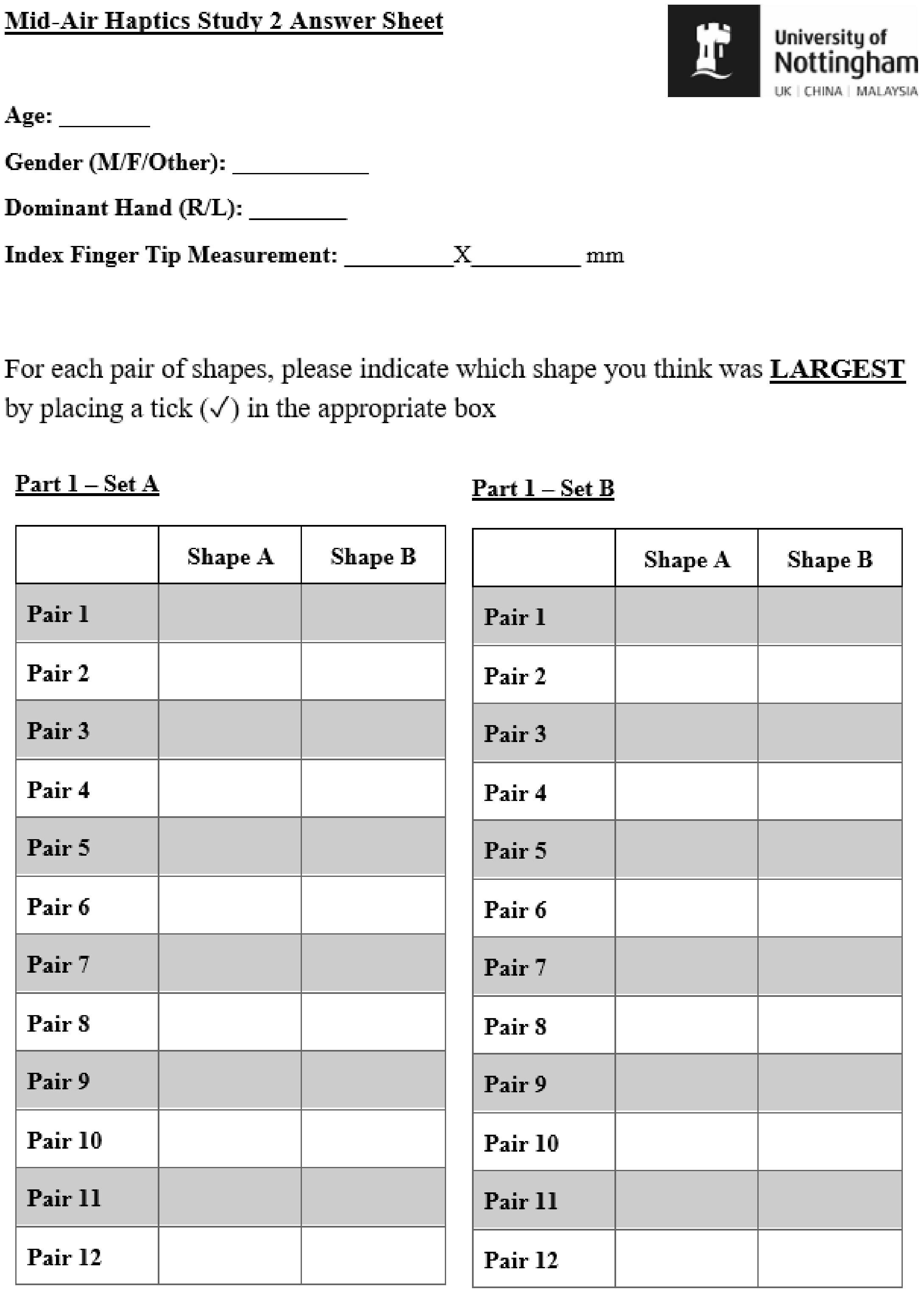
Date: _______________

Participant Signature: ____________________________

Researcher Name: James Khan

Researcher Signature: ____________________________

3: Answer sheet given to participants during the shape size discrimination task (does not include all answer fields) – Study 2



Mid-Air Haptics Study 2 Answer Sheet

University of Nottingham
UK | CHINA | MALAYSIA

Age: ________

Gender (M/F/Other): ____________

Dominant Hand (R/L): ________

Index Finger Tip Measurement: _________X_________ mm

For each pair of shapes, please indicate which shape you think was **LARGEST** by placing a tick (✓) in the appropriate box

Part 1 – Set A

	Shape A	**Shape B**
Pair 1		
Pair 2		
Pair 3		
Pair 4		
Pair 5		
Pair 6		
Pair 7		
Pair 8		
Pair 9		
Pair 10		
Pair 11		
Pair 12		

Part 1 – Set B

	Shape A	**Shape B**
Pair 1		
Pair 2		
Pair 3		
Pair 4		
Pair 5		
Pair 6		
Pair 7		
Pair 8		
Pair 9		
Pair 10		
Pair 11		
Pair 12		

4: Answer sheet given to participants for the tactile threshold task – Study 2

Part 2

In this section you will be presented with one shape at different intensities. Please record whether you can feel the shape by placing a tick (✓) in the appropriate box

	Yes	No
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
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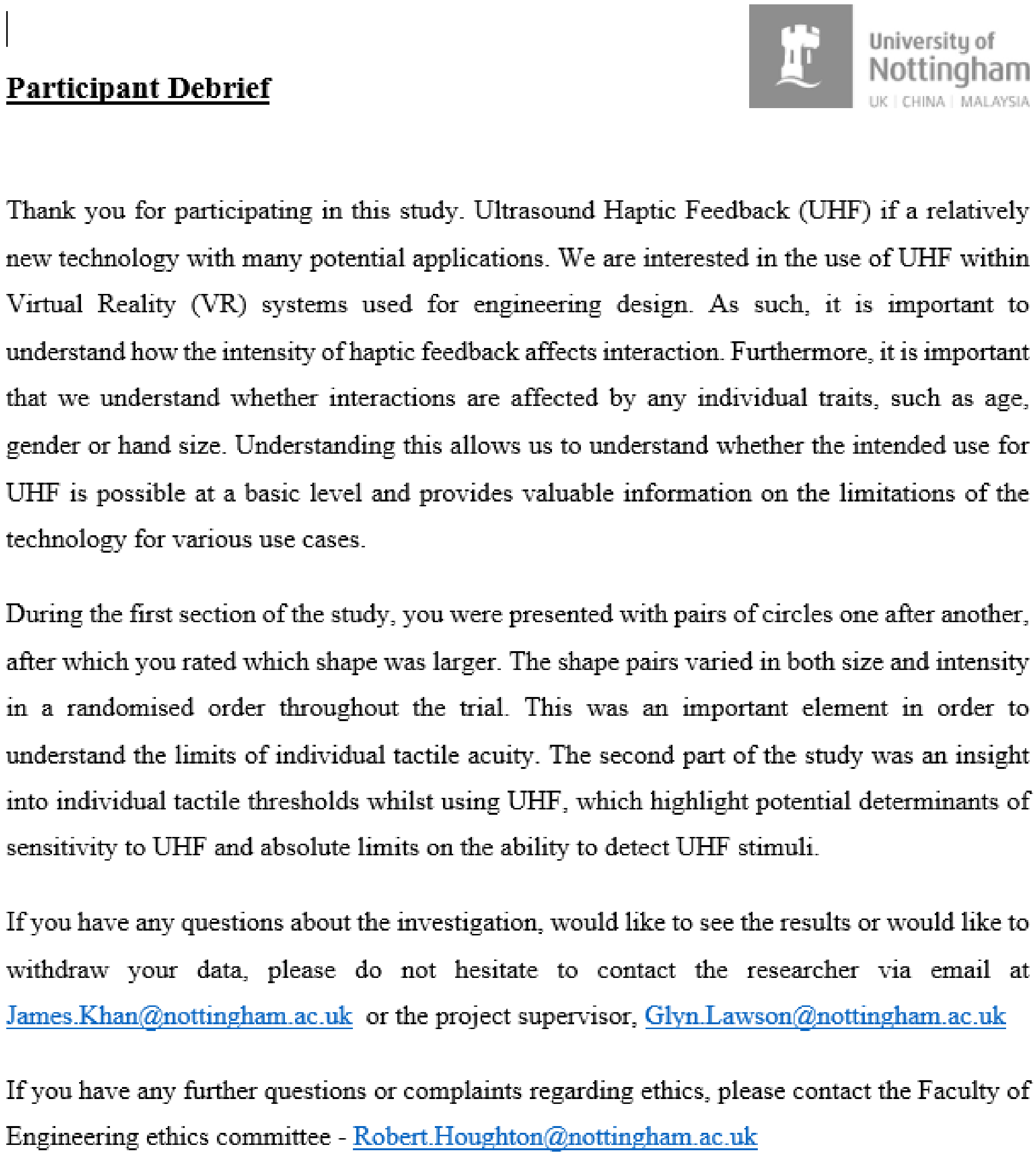
21		
22		

5: Debrief given to participants after taking part (Study 2)



Participant Debrief

Thank you for participating in this study. Ultrasound Haptic Feedback (UHF) if a relatively new technology with many potential applications. We are interested in the use of UHF within Virtual Reality (VR) systems used for engineering design. As such, it is important to understand how the intensity of haptic feedback affects interaction. Furthermore, it is important that we understand whether interactions are affected by any individual traits, such as age, gender or hand size. Understanding this allows us to understand whether the intended use for UHF is possible at a basic level and provides valuable information on the limitations of the technology for various use cases.

During the first section of the study, you were presented with pairs of circles one after another, after which you rated which shape was larger. The shape pairs varied in both size and intensity in a randomised order throughout the trial. This was an important element in order to understand the limits of individual tactile acuity. The second part of the study was an insight into individual tactile thresholds whilst using UHF, which highlight potential determinants of sensitivity to UHF and absolute limits on the ability to detect UHF stimuli.

If you have any questions about the investigation, would like to see the results or would like to withdraw your data, please do not hesitate to contact the researcher via email at James.Khan@nottingham.ac.uk or the project supervisor, Glyn.Lawson@nottingham.ac.uk

If you have any further questions or complaints regarding ethics, please contact the Faculty of Engineering ethics committee - Robert.Houghton@nottingham.ac.uk

Appendix C: Supplementary materials used during Study 3

1: Study brief given to participants before taking part – Study 3

Participant Brief

For this investigation we are interested in subjective differences in the use of Ultrasound Haptic Feedback (UHF). UHF is a technology that uses ultrasound to create 'haptic' or touch feedback in mid-air, without physical contact with a surface or any visual feedback.

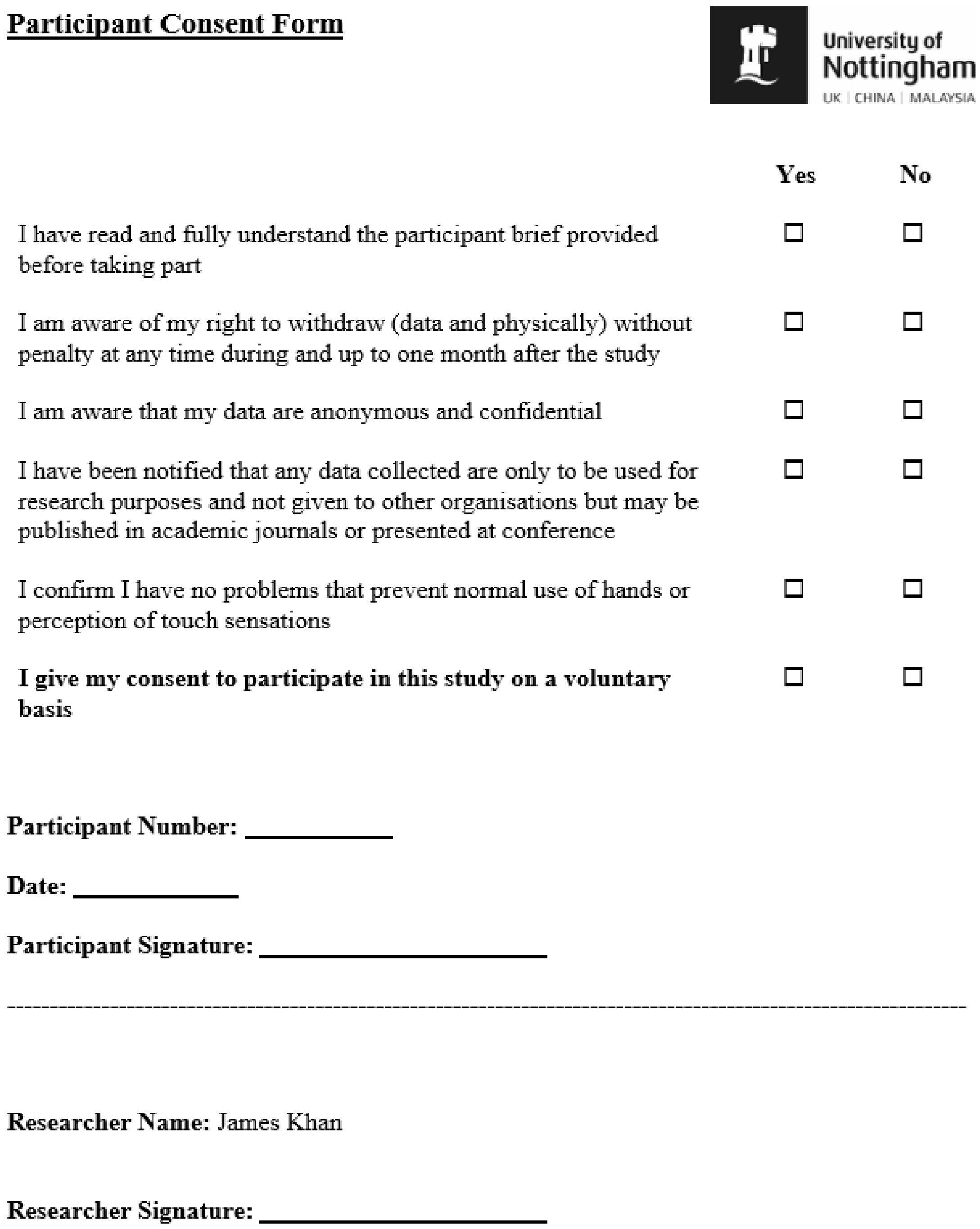
Firstly, if you agree to take part, you will be asked to sign the provided consent form and fill in some details about yourself that will be kept confidential and anonymous. Before starting we need to take measurements of your index finger tip, this gives information about the number of tactile receptors in the fingers. During the study, you will need to wear headphones playing white noise in order to mask any sounds the ultrasound array makes. Before starting the trials, you will be given a short practice during which you can feel and acclimatise yourself to the sensation of ultrasound haptic feedback. Once completed, the first task will start.

During the task, you will be presented with pairs of circles in mid-air (one circle projected at a time), the two circles **may** differ in size. Using **ONLY** your dominant hand, your task is to discern which object is larger, if any **(A or B)** and place a tick in the corresponding box on the answer on the sheet provided. If you think the shapes are the same size, tick the **"NO DIFFERENCE"** box. You will be given verbal prompts as to which shape you are currently experiencing. The task does not require speed, however, you are encouraged to answer as quickly as possible whilst being able to provide accurate answers. You will not see the shapes during the task, you will only feel them.

Your data will be reported as part of a set and individuals will not be recognisable. The data will also remain stored in a locked computer data file accessible only by the researcher and project supervisor. These data will only be used for research purposes for a PhD project in conjunction with an industry partner. You are able to withdraw at any point without penalty. If you wish to withdraw, please tell the experimenter. After withdrawal, your data will be removed from the study and destroyed. You have up to one month after taking part to request the removal of your data should you wish to do so. You can do this by contacting the researcher, via email – James.Khan@nottingham.ac.uk or the project supervisor, Glyn.Lawson@nottingham.ac.uk

If you have any further questions or complaints regarding ethics, please contact the Faculty of Engineering ethics committee – Robert.Houghton@nottingham.ac.uk

2: Consent form given to participants before taking part – Study 3



Participant Consent Form

	Yes	No
I have read and fully understand the participant brief provided before taking part	☐	☐
I am aware of my right to withdraw (data and physically) without penalty at any time during and up to one month after the study	☐	☐
I am aware that my data are anonymous and confidential	☐	☐
I have been notified that any data collected are only to be used for research purposes and not given to other organisations but may be published in academic journals or presented at conference	☐	☐
I confirm I have no problems that prevent normal use of hands or perception of touch sensations	☐	☐
I give my consent to participate in this study on a voluntary basis	☐	☐

Participant Number: ____________

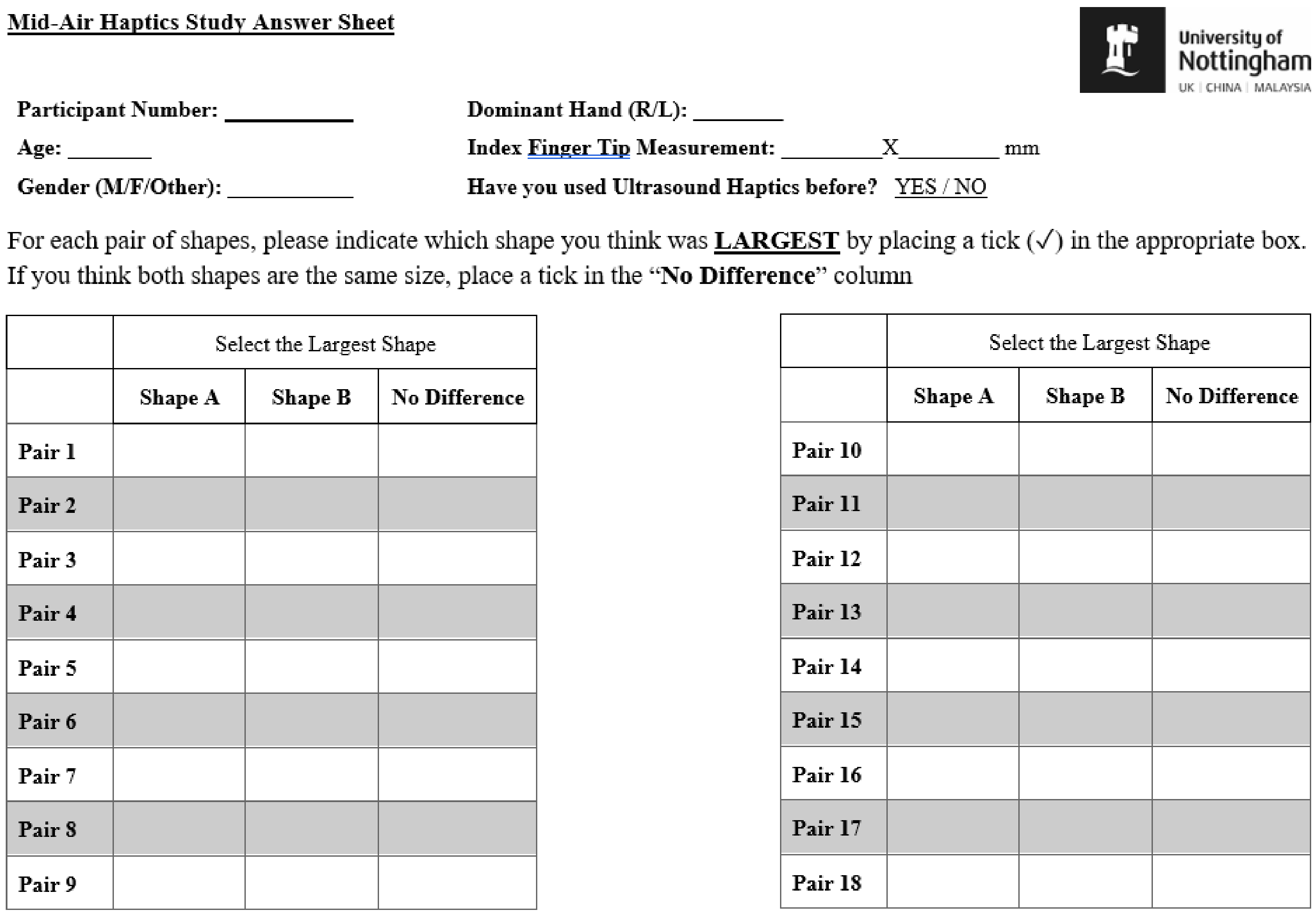
Date: ______________

Participant Signature: ________________________

Researcher Name: James Khan

Researcher Signature: ________________________

3: Answer sheet given to participants (does not show all answer fields) – Study 3



Mid-Air Haptics Study Answer Sheet

University of Nottingham
UK | CHINA | MALAYSIA

Participant Number: ___________
Age: ________
Gender (M/F/Other): ___________

Dominant Hand (R/L): ________
Index Finger Tip Measurement: _________X_________ mm
Have you used Ultrasound Haptics before? YES / NO

For each pair of shapes, please indicate which shape you think was **LARGEST** by placing a tick (✓) in the appropriate box. If you think both shapes are the same size, place a tick in the “**No Difference**” column

	Select the Largest Shape		
	Shape A	**Shape B**	**No Difference**
Pair 1			
Pair 2			
Pair 3			
Pair 4			
Pair 5			
Pair 6			
Pair 7			
Pair 8			
Pair 9			

	Select the Largest Shape		
	Shape A	**Shape B**	**No Difference**
Pair 10			
Pair 11			
Pair 12			
Pair 13			
Pair 14			
Pair 15			
Pair 16			
Pair 17			
Pair 18			

4: Debrief given to participants after taking part – Study 3

Participant Debrief

Thank you for participating in this study. Ultrasound Haptic Feedback (UHF) if a relatively new technology with many potential applications. We are interested in the use of UHF within Virtual Reality (VR) systems used for engineering design. As such, it is important to understand how the intensity of haptic feedback affects interaction. Furthermore, it is important that we understand whether interactions are affected by any individual traits, such as age, gender or hand size. Understanding this allows us to determine whether the intended use for UHF is possible at a basic level and provides valuable information on the limitations of the technology for various use cases.

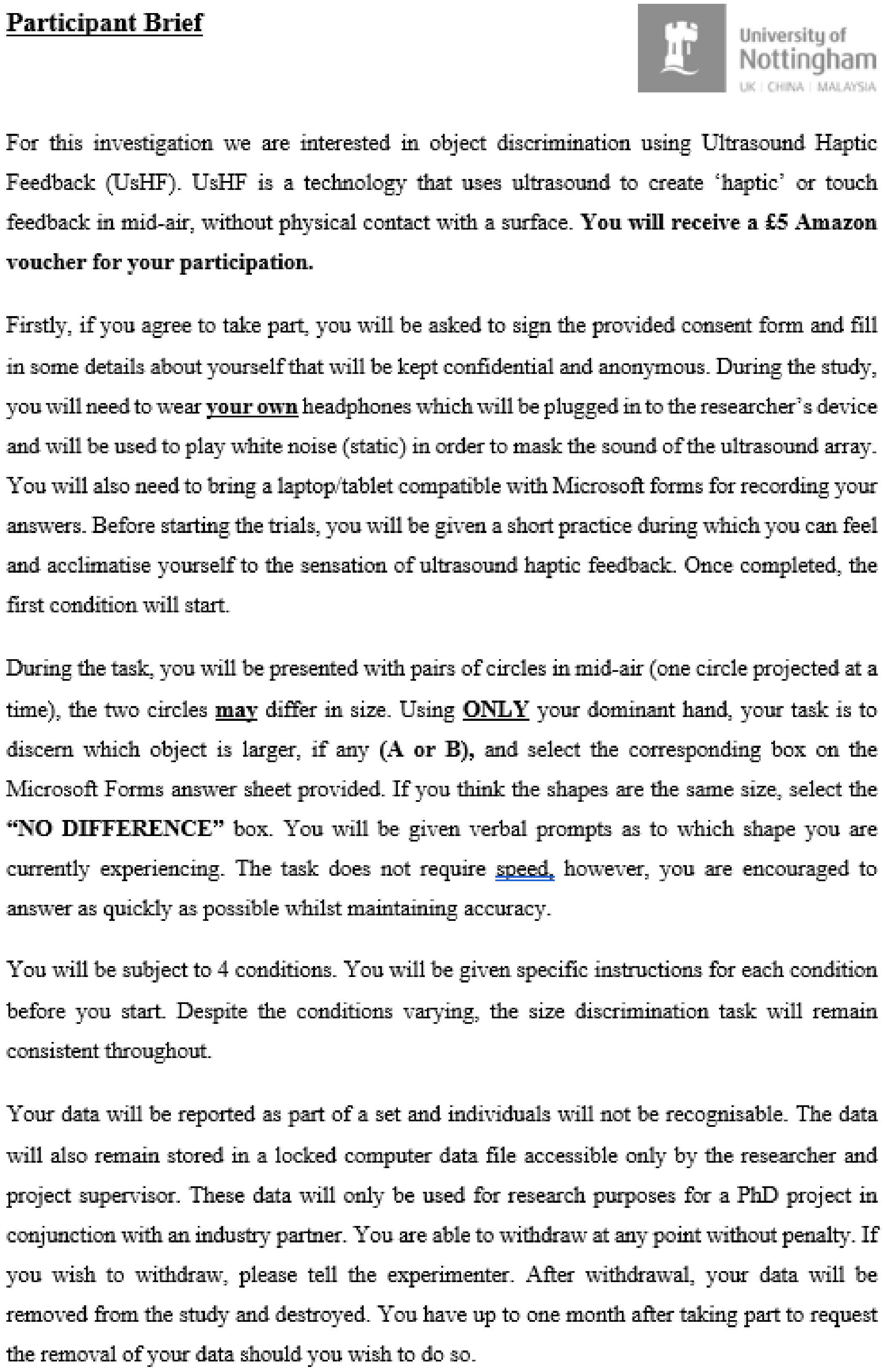
During the study, you were presented with pairs of circles, after which you rated which shape highlighted whether one shape was larger than the other, or whether they were both the same. The shape pairs varied in both size and intensity in a randomised order throughout the trial. Anecdotal evidence has suggested that intensity is directly interfering with exploration of mid-air objects, and thus, users are focussing on intensity as a que for object size. If these findings are borne out during the current study, further considerations will need to be made about the way UHF is implemented. For example, findings of this nature could mean virtual objects need not be rendered in high fidelity or as an accurate depiction.

If you have any questions about the investigation, would like to see the results or would like to withdraw your data, please do not hesitate to contact the researcher via email at James.Khan@nottingham.ac.uk or the project supervisor, Glyn.Lawson@nottingham.ac.uk

If you have any further questions or complaints regarding ethics, please contact the Faculty of Engineering ethics committee - Robert.Houghton@nottingham.ac.uk

Appendix D: Supplementary materials used during Study 4

1: Study brief given to participants before taking part – Study 4



Participant Brief

University of Nottingham
UK | CHINA | MALAYSIA

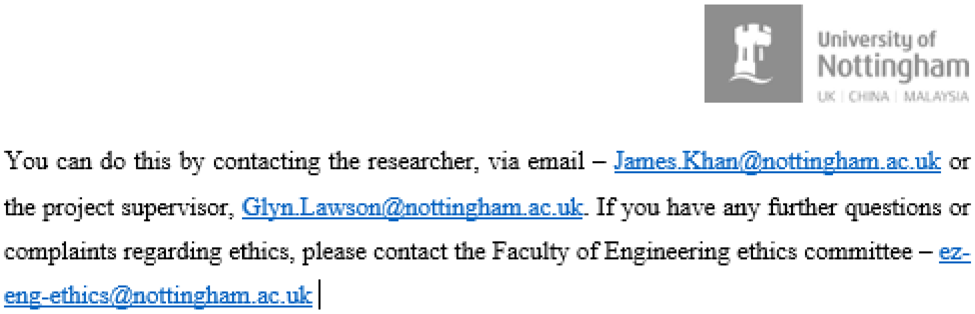
For this investigation we are interested in object discrimination using Ultrasound Haptic Feedback (UsHF). UsHF is a technology that uses ultrasound to create 'haptic' or touch feedback in mid-air, without physical contact with a surface. **You will receive a £5 Amazon voucher for your participation.**

Firstly, if you agree to take part, you will be asked to sign the provided consent form and fill in some details about yourself that will be kept confidential and anonymous. During the study, you will need to wear **your own** headphones which will be plugged in to the researcher's device and will be used to play white noise (static) in order to mask the sound of the ultrasound array. You will also need to bring a laptop/tablet compatible with Microsoft forms for recording your answers. Before starting the trials, you will be given a short practice during which you can feel and acclimatise yourself to the sensation of ultrasound haptic feedback. Once completed, the first condition will start.

During the task, you will be presented with pairs of circles in mid-air (one circle projected at a time), the two circles **may** differ in size. Using **ONLY** your dominant hand, your task is to discern which object is larger, if any **(A or B),** and select the corresponding box on the Microsoft Forms answer sheet provided. If you think the shapes are the same size, select the **"NO DIFFERENCE"** box. You will be given verbal prompts as to which shape you are currently experiencing. The task does not require speed, however, you are encouraged to answer as quickly as possible whilst maintaining accuracy.

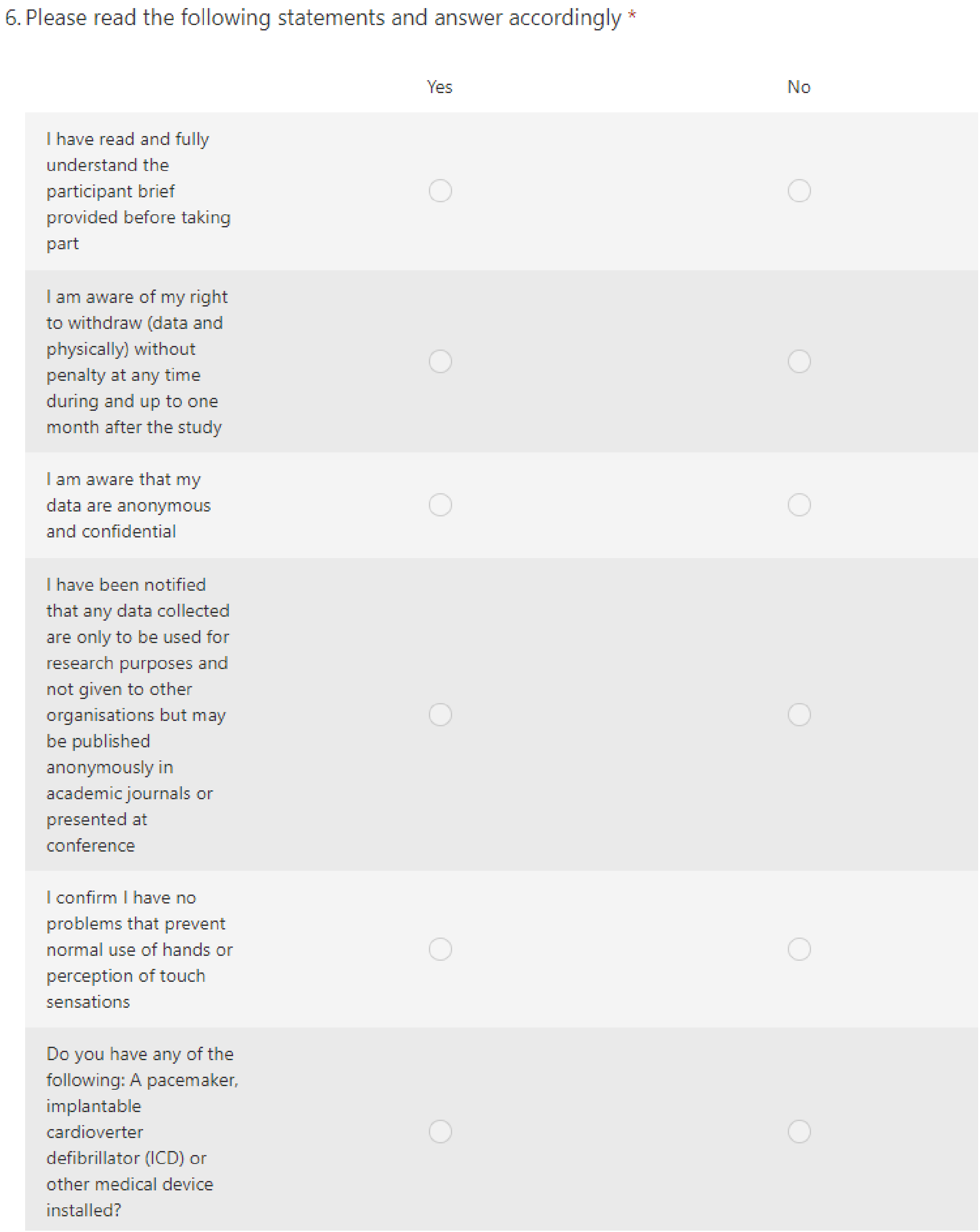
You will be subject to 4 conditions. You will be given specific instructions for each condition before you start. Despite the conditions varying, the size discrimination task will remain consistent throughout.

Your data will be reported as part of a set and individuals will not be recognisable. The data will also remain stored in a locked computer data file accessible only by the researcher and project supervisor. These data will only be used for research purposes for a PhD project in conjunction with an industry partner. You are able to withdraw at any point without penalty. If you wish to withdraw, please tell the experimenter. After withdrawal, your data will be removed from the study and destroyed. You have up to one month after taking part to request the removal of your data should you wish to do so.



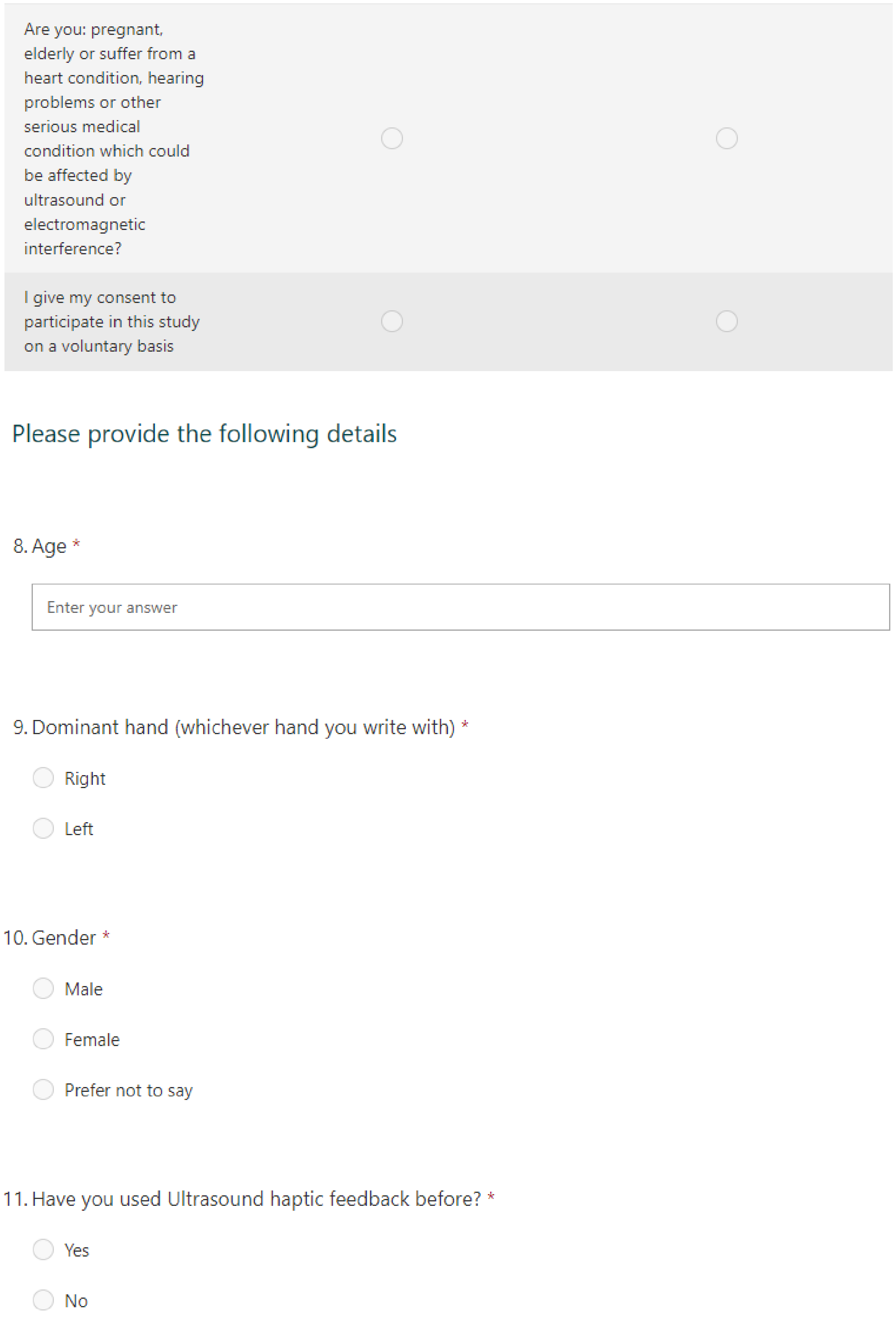
You can do this by contacting the researcher, via email – James.Khan@nottingham.ac.uk or the project supervisor, Glyn.Lawson@nottingham.ac.uk. If you have any further questions or complaints regarding ethics, please contact the Faculty of Engineering ethics committee – ez-eng-ethics@nottingham.ac.uk

2: Consent form given to participants before taking part – Study 4



6. Please read the following statements and answer accordingly *

	Yes	No
I have read and fully understand the participant brief provided before taking part	○	○
I am aware of my right to withdraw (data and physically) without penalty at any time during and up to one month after the study	○	○
I am aware that my data are anonymous and confidential	○	○
I have been notified that any data collected are only to be used for research purposes and not given to other organisations but may be published anonymously in academic journals or presented at conference	○	○
I confirm I have no problems that prevent normal use of hands or perception of touch sensations	○	○
Do you have any of the following: A pacemaker, implantable cardioverter defibrillator (ICD) or other medical device installed?	○	○



Are you: pregnant, elderly or suffer from a heart condition, hearing problems or other serious medical condition which could be affected by ultrasound or electromagnetic interference?	○	○
I give my consent to participate in this study on a voluntary basis	○	○

Please provide the following details

8. Age *

Enter your answer

9. Dominant hand (whichever hand you write with) *

○ Right

○ Left

10. Gender *

○ Male

○ Female

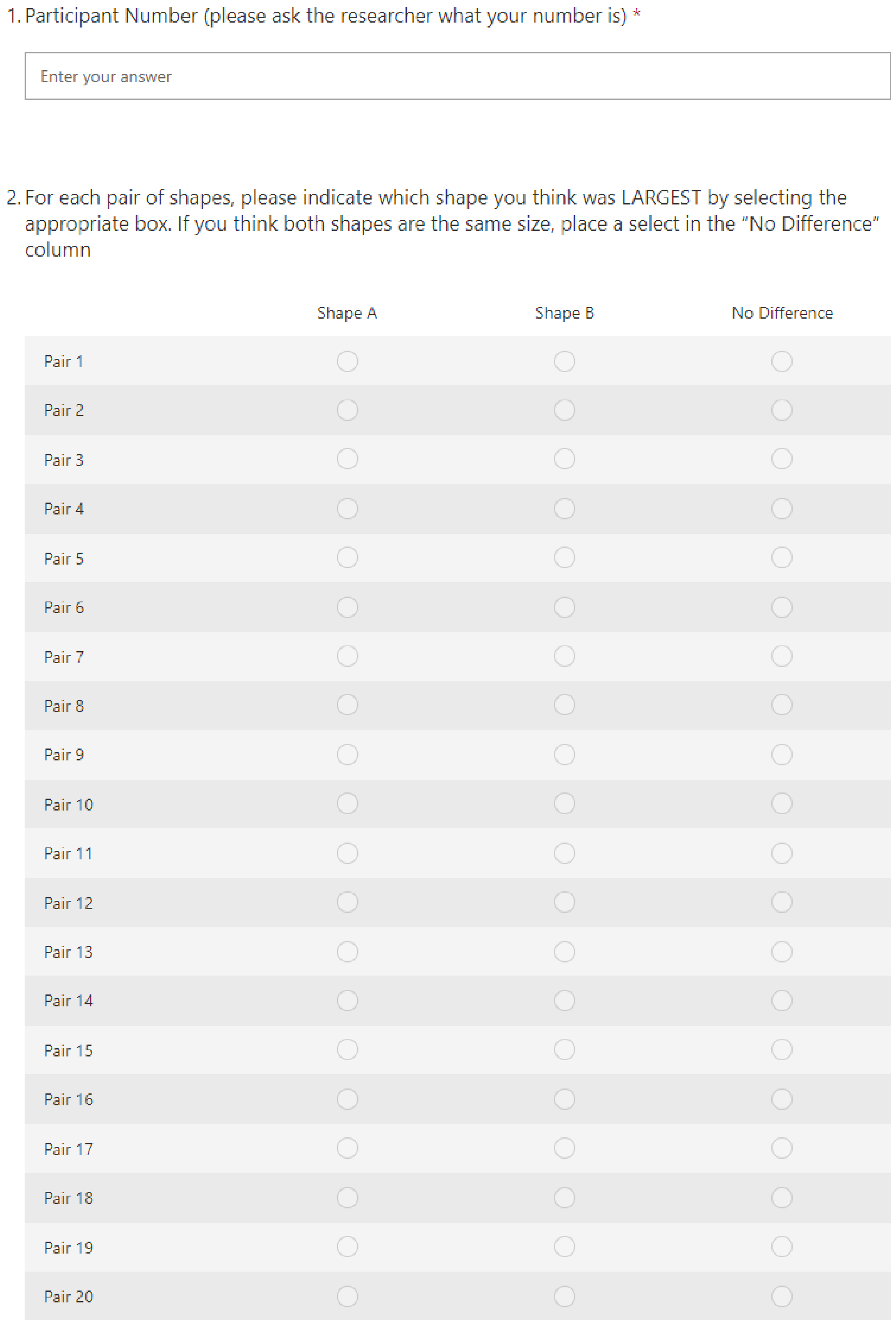
○ Prefer not to say

11. Have you used Ultrasound haptic feedback before? *

○ Yes

○ No

3: An example answer sheet used to record participant answers. Does not include all answer fields – Study 4



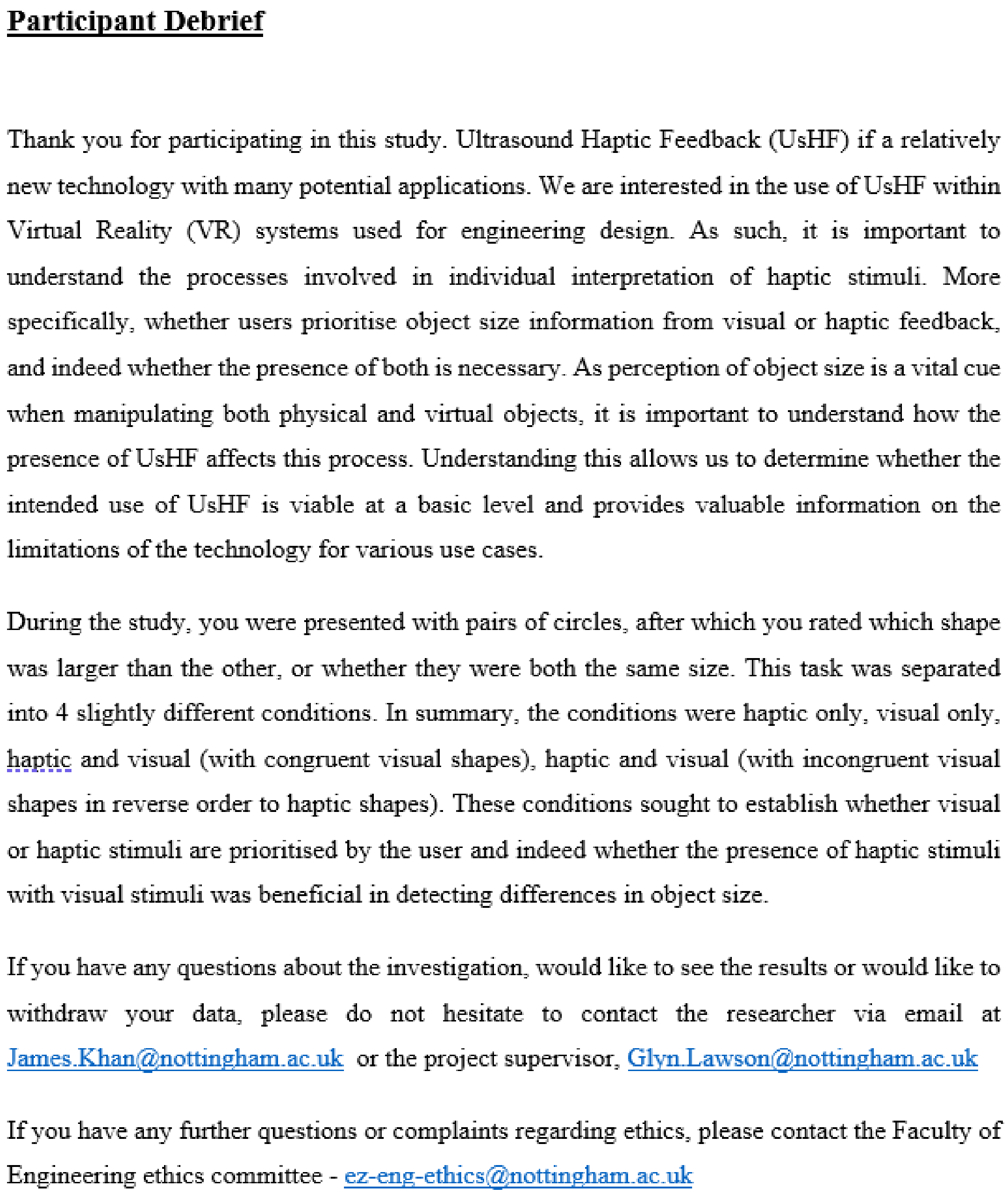
1. Participant Number (please ask the researcher what your number is) *

Enter your answer

2. For each pair of shapes, please indicate which shape you think was LARGEST by selecting the appropriate box. If you think both shapes are the same size, place a select in the "No Difference" column

	Shape A	Shape B	No Difference
Pair 1	○	○	○
Pair 2	○	○	○
Pair 3	○	○	○
Pair 4	○	○	○
Pair 5	○	○	○
Pair 6	○	○	○
Pair 7	○	○	○
Pair 8	○	○	○
Pair 9	○	○	○
Pair 10	○	○	○
Pair 11	○	○	○
Pair 12	○	○	○
Pair 13	○	○	○
Pair 14	○	○	○
Pair 15	○	○	○
Pair 16	○	○	○
Pair 17	○	○	○
Pair 18	○	○	○
Pair 19	○	○	○
Pair 20	○	○	○

4: Debrief given to participants after taking part – Study 4



Participant Debrief

Thank you for participating in this study. Ultrasound Haptic Feedback (UsHF) if a relatively new technology with many potential applications. We are interested in the use of UsHF within Virtual Reality (VR) systems used for engineering design. As such, it is important to understand the processes involved in individual interpretation of haptic stimuli. More specifically, whether users prioritise object size information from visual or haptic feedback, and indeed whether the presence of both is necessary. As perception of object size is a vital cue when manipulating both physical and virtual objects, it is important to understand how the presence of UsHF affects this process. Understanding this allows us to determine whether the intended use of UsHF is viable at a basic level and provides valuable information on the limitations of the technology for various use cases.

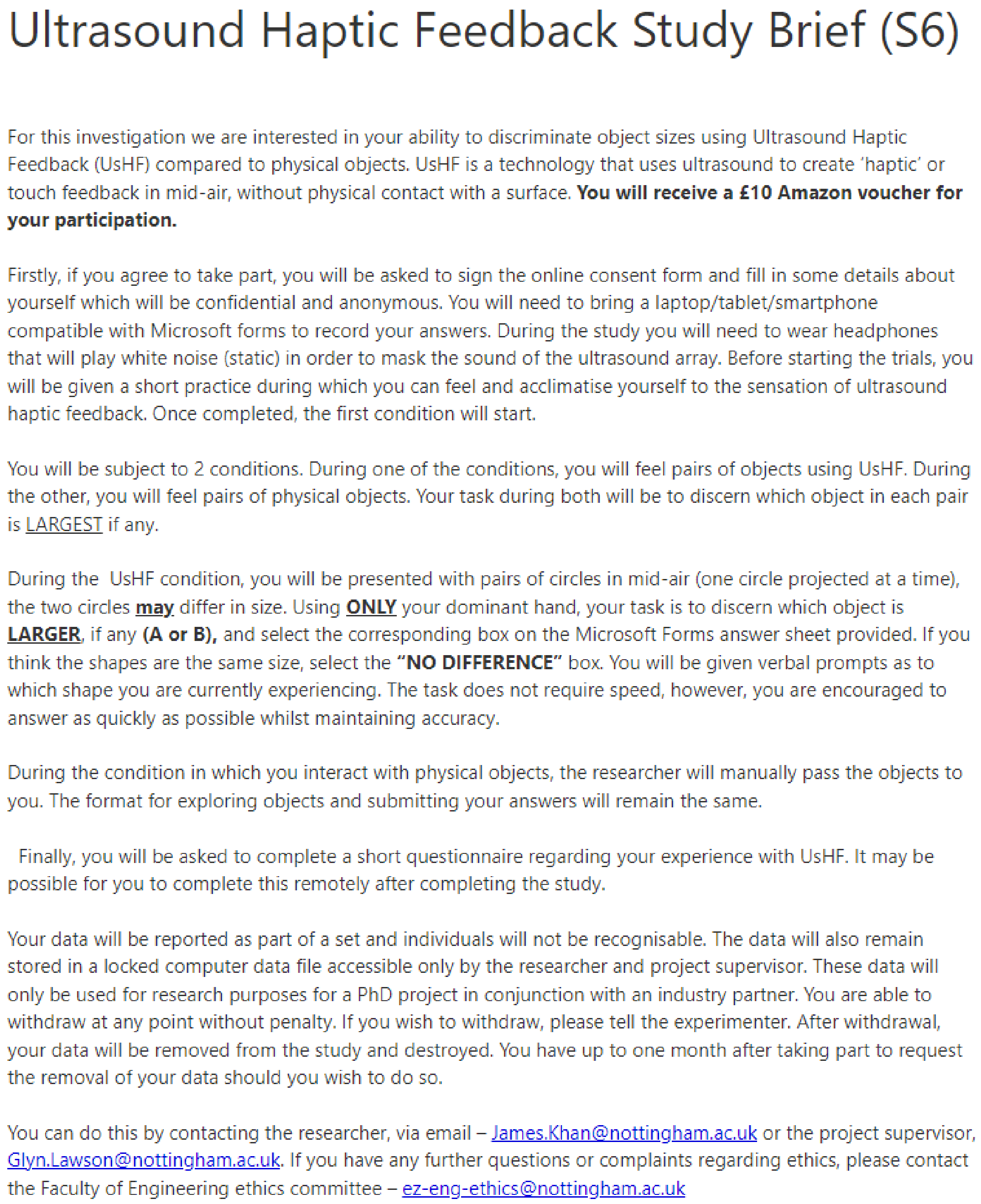
During the study, you were presented with pairs of circles, after which you rated which shape was larger than the other, or whether they were both the same size. This task was separated into 4 slightly different conditions. In summary, the conditions were haptic only, visual only, haptic and visual (with congruent visual shapes), haptic and visual (with incongruent visual shapes in reverse order to haptic shapes). These conditions sought to establish whether visual or haptic stimuli are prioritised by the user and indeed whether the presence of haptic stimuli with visual stimuli was beneficial in detecting differences in object size.

If you have any questions about the investigation, would like to see the results or would like to withdraw your data, please do not hesitate to contact the researcher via email at James.Khan@nottingham.ac.uk or the project supervisor, Glyn.Lawson@nottingham.ac.uk

If you have any further questions or complaints regarding ethics, please contact the Faculty of Engineering ethics committee - ez-eng-ethics@nottingham.ac.uk

Appendix E: Supplementary materials used during Study 5

1: Brief given to participants before taking part – Study 5



Ultrasound Haptic Feedback Study Brief (S6)

For this investigation we are interested in your ability to discriminate object sizes using Ultrasound Haptic Feedback (UsHF) compared to physical objects. UsHF is a technology that uses ultrasound to create 'haptic' or touch feedback in mid-air, without physical contact with a surface. **You will receive a £10 Amazon voucher for your participation.**

Firstly, if you agree to take part, you will be asked to sign the online consent form and fill in some details about yourself which will be confidential and anonymous. You will need to bring a laptop/tablet/smartphone compatible with Microsoft forms to record your answers. During the study you will need to wear headphones that will play white noise (static) in order to mask the sound of the ultrasound array. Before starting the trials, you will be given a short practice during which you can feel and acclimatise yourself to the sensation of ultrasound haptic feedback. Once completed, the first condition will start.

You will be subject to 2 conditions. During one of the conditions, you will feel pairs of objects using UsHF. During the other, you will feel pairs of physical objects. Your task during both will be to discern which object in each pair is LARGEST if any.

During the UsHF condition, you will be presented with pairs of circles in mid-air (one circle projected at a time), the two circles **may** differ in size. Using **ONLY** your dominant hand, your task is to discern which object is **LARGER**, if any **(A or B),** and select the corresponding box on the Microsoft Forms answer sheet provided. If you think the shapes are the same size, select the **"NO DIFFERENCE"** box. You will be given verbal prompts as to which shape you are currently experiencing. The task does not require speed, however, you are encouraged to answer as quickly as possible whilst maintaining accuracy.

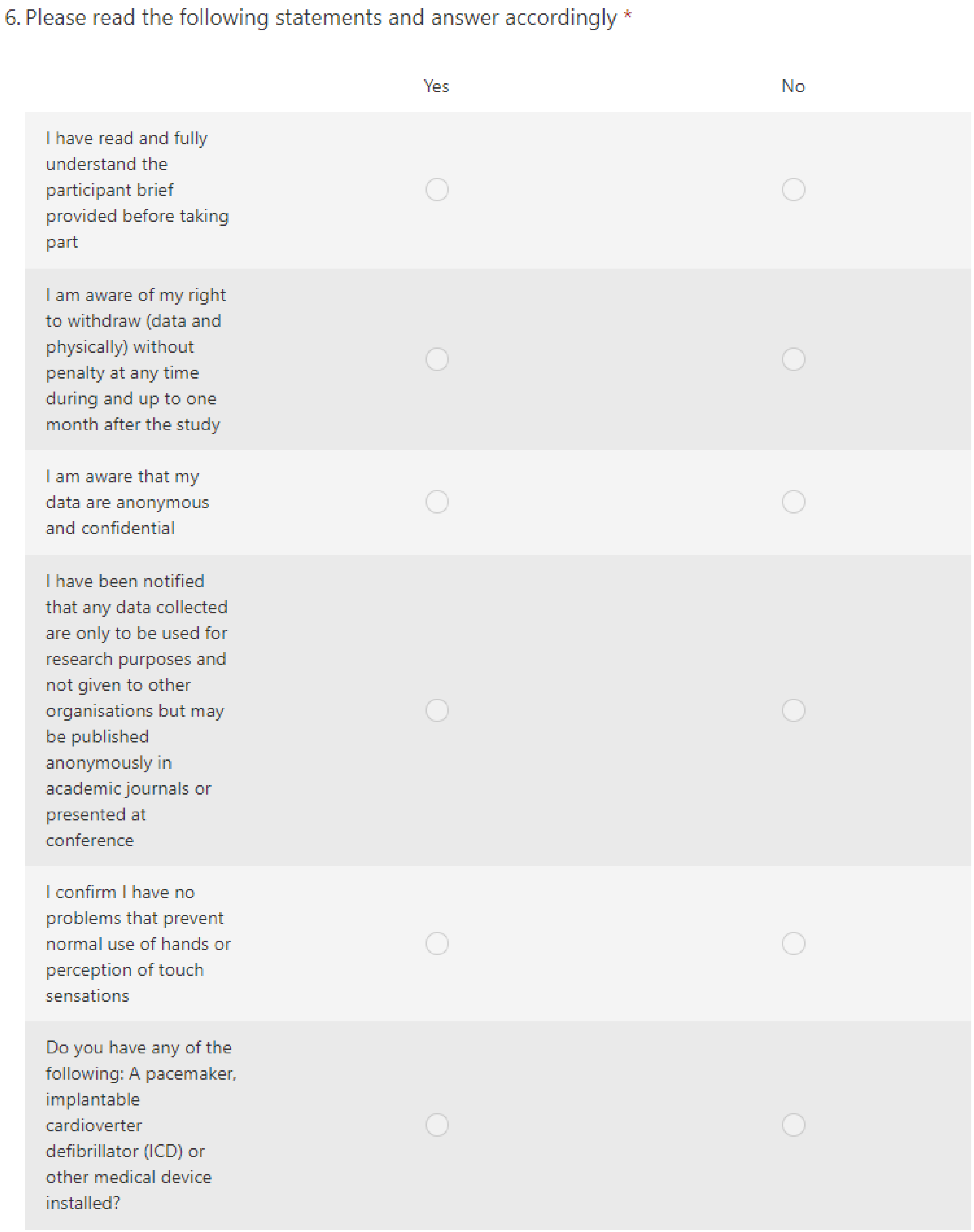
During the condition in which you interact with physical objects, the researcher will manually pass the objects to you. The format for exploring objects and submitting your answers will remain the same.

Finally, you will be asked to complete a short questionnaire regarding your experience with UsHF. It may be possible for you to complete this remotely after completing the study.

Your data will be reported as part of a set and individuals will not be recognisable. The data will also remain stored in a locked computer data file accessible only by the researcher and project supervisor. These data will only be used for research purposes for a PhD project in conjunction with an industry partner. You are able to withdraw at any point without penalty. If you wish to withdraw, please tell the experimenter. After withdrawal, your data will be removed from the study and destroyed. You have up to one month after taking part to request the removal of your data should you wish to do so.

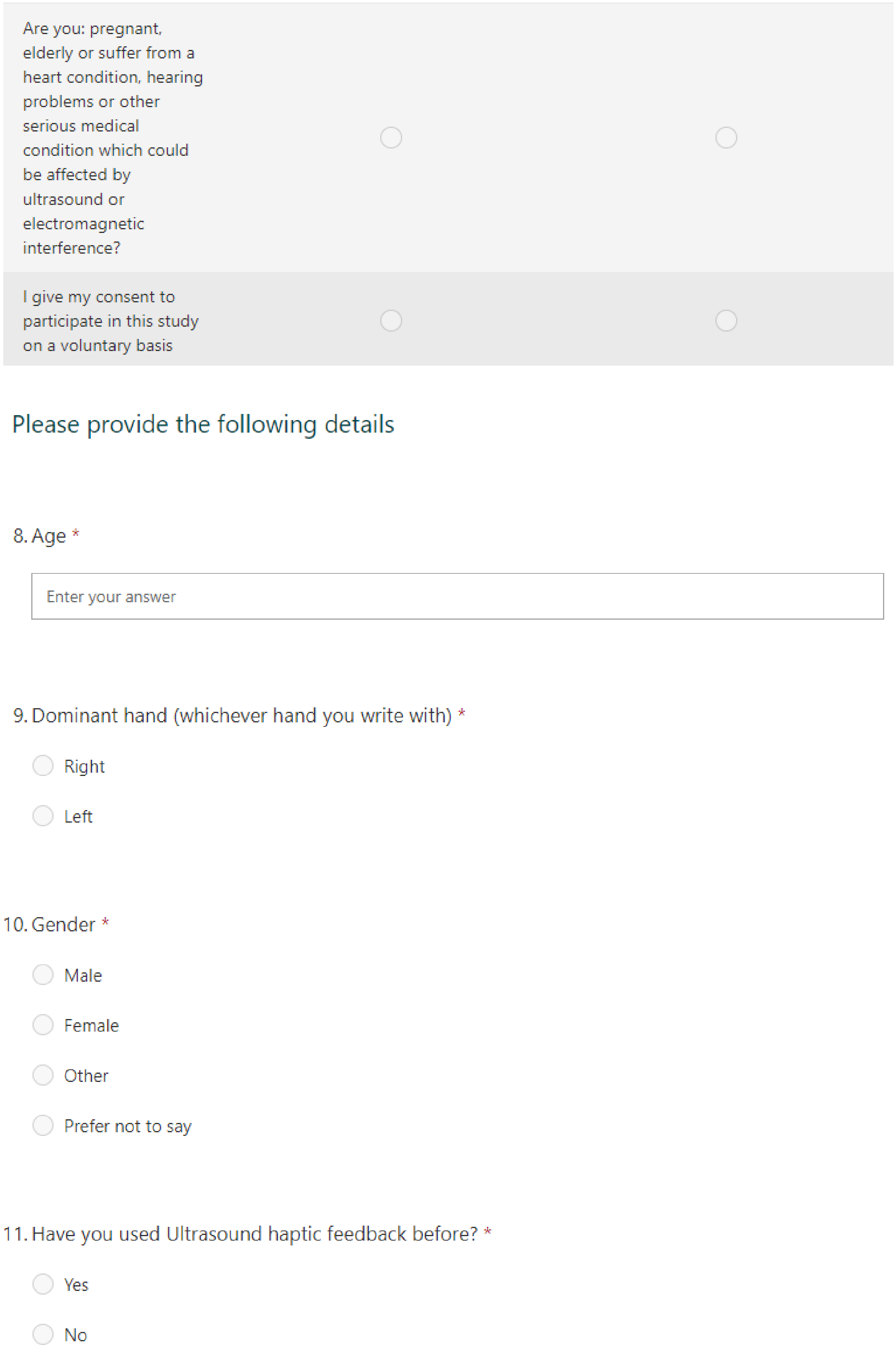
You can do this by contacting the researcher, via email – James.Khan@nottingham.ac.uk or the project supervisor, Glyn.Lawson@nottingham.ac.uk. If you have any further questions or complaints regarding ethics, please contact the Faculty of Engineering ethics committee – ez-eng-ethics@nottingham.ac.uk

2: Consent form given to participants before taking part – Study 5



6. Please read the following statements and answer accordingly *

	Yes	No
I have read and fully understand the participant brief provided before taking part	○	○
I am aware of my right to withdraw (data and physically) without penalty at any time during and up to one month after the study	○	○
I am aware that my data are anonymous and confidential	○	○
I have been notified that any data collected are only to be used for research purposes and not given to other organisations but may be published anonymously in academic journals or presented at conference	○	○
I confirm I have no problems that prevent normal use of hands or perception of touch sensations	○	○
Do you have any of the following: A pacemaker, implantable cardioverter defibrillator (ICD) or other medical device installed?	○	○



Are you: pregnant, elderly or suffer from a heart condition, hearing problems or other serious medical condition which could be affected by ultrasound or electromagnetic interference?	○	○
I give my consent to participate in this study on a voluntary basis	○	○

Please provide the following details

8. Age *

Enter your answer

9. Dominant hand (whichever hand you write with) *

○ Right

○ Left

10. Gender *

○ Male

○ Female

○ Other

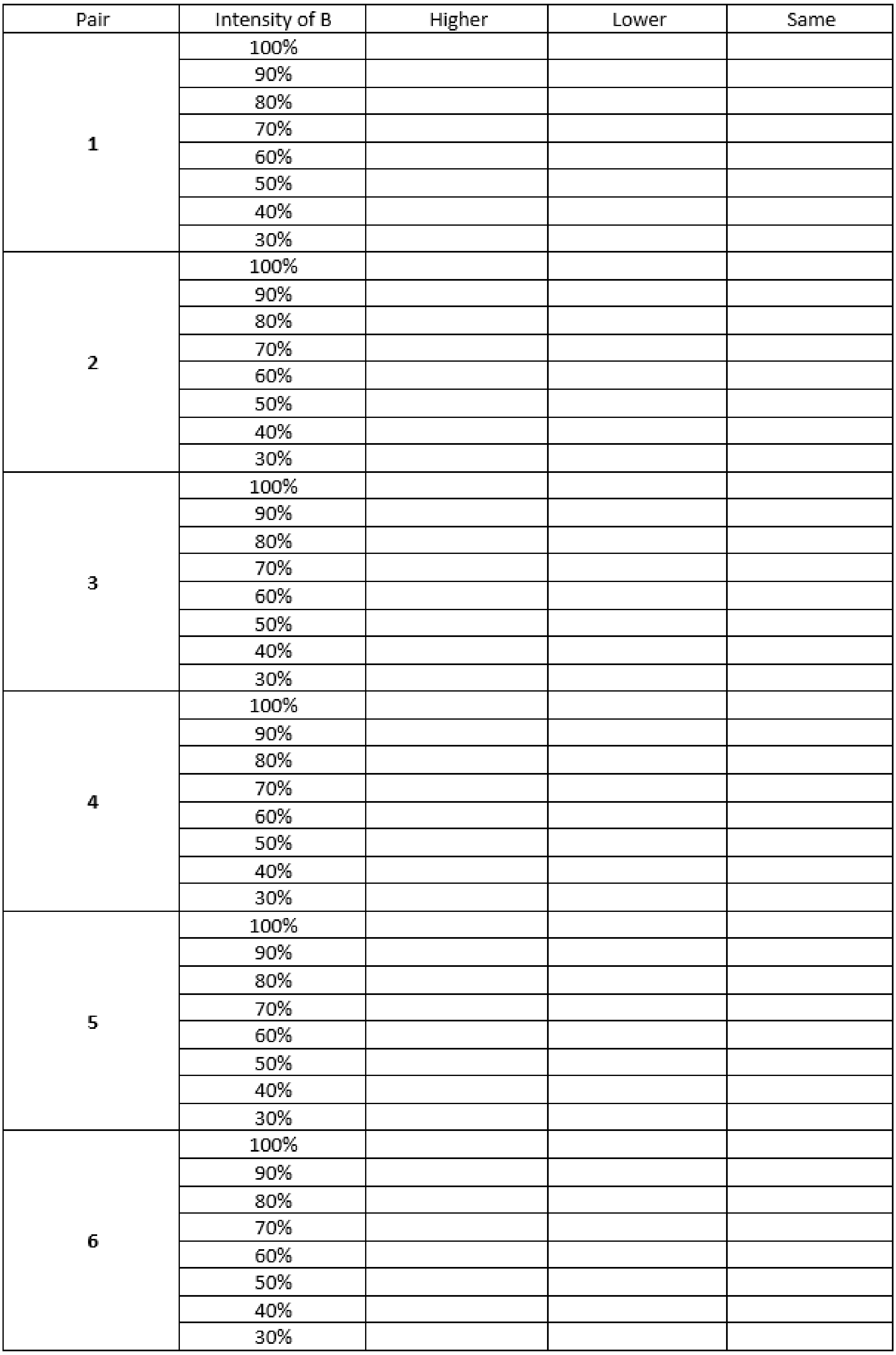
○ Prefer not to say

11. Have you used Ultrasound haptic feedback before? *

○ Yes

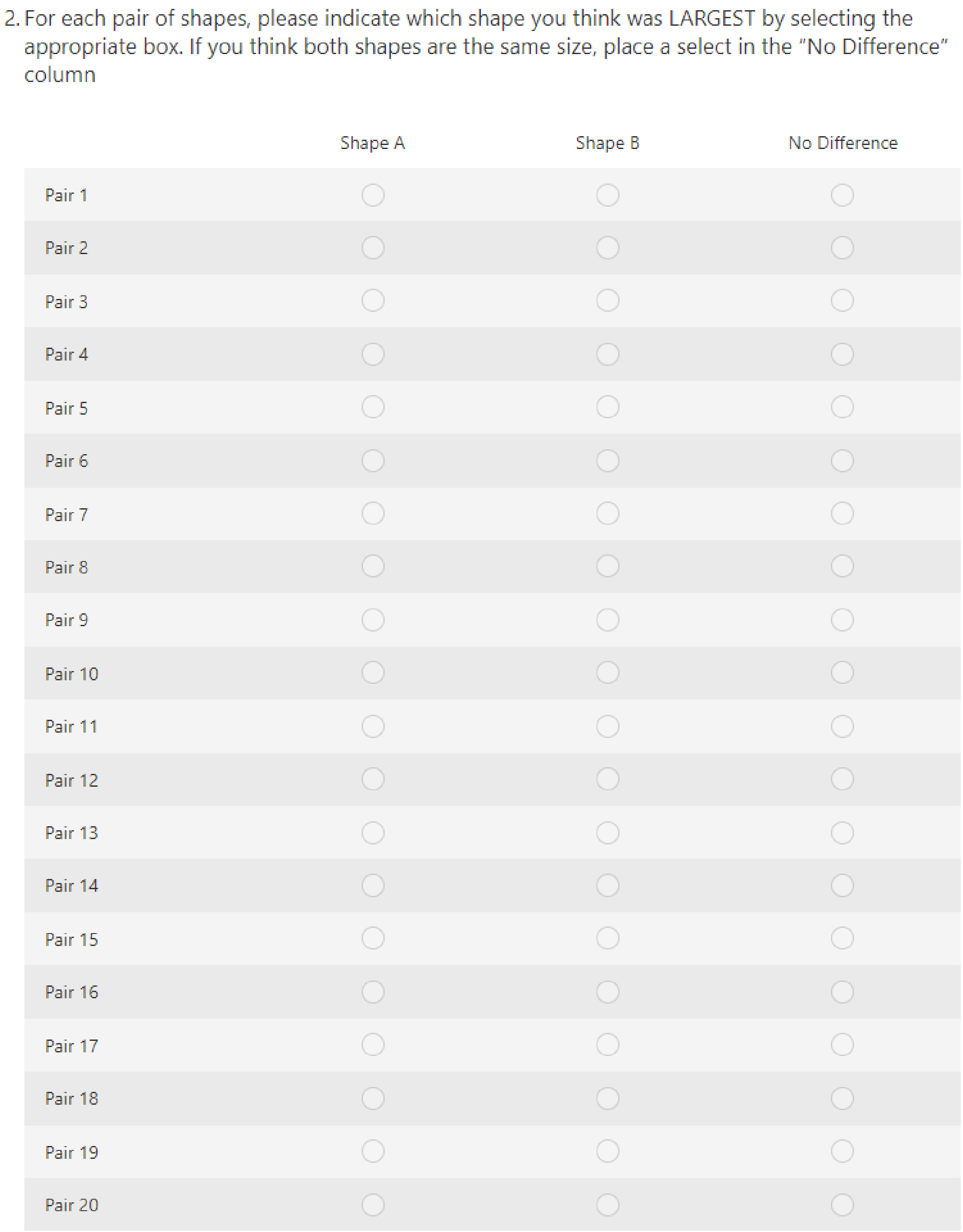
○ No

3: Answer sheet given to participants during the intensity normalisation experiment – Study 5



Pair	Intensity of B	Higher	Lower	Same
1	100%			
	90%			
	80%			
	70%			
	60%			
	50%			
	40%			
	30%			
2	100%			
	90%			
	80%			
	70%			
	60%			
	50%			
	40%			
	30%			
3	100%			
	90%			
	80%			
	70%			
	60%			
	50%			
	40%			
	30%			
4	100%			
	90%			
	80%			
	70%			
	60%			
	50%			
	40%			
	30%			
5	100%			
	90%			
	80%			
	70%			
	60%			
	50%			
	40%			
	30%			
6	100%			
	90%			
	80%			
	70%			
	60%			
	50%			
	40%			
	30%			

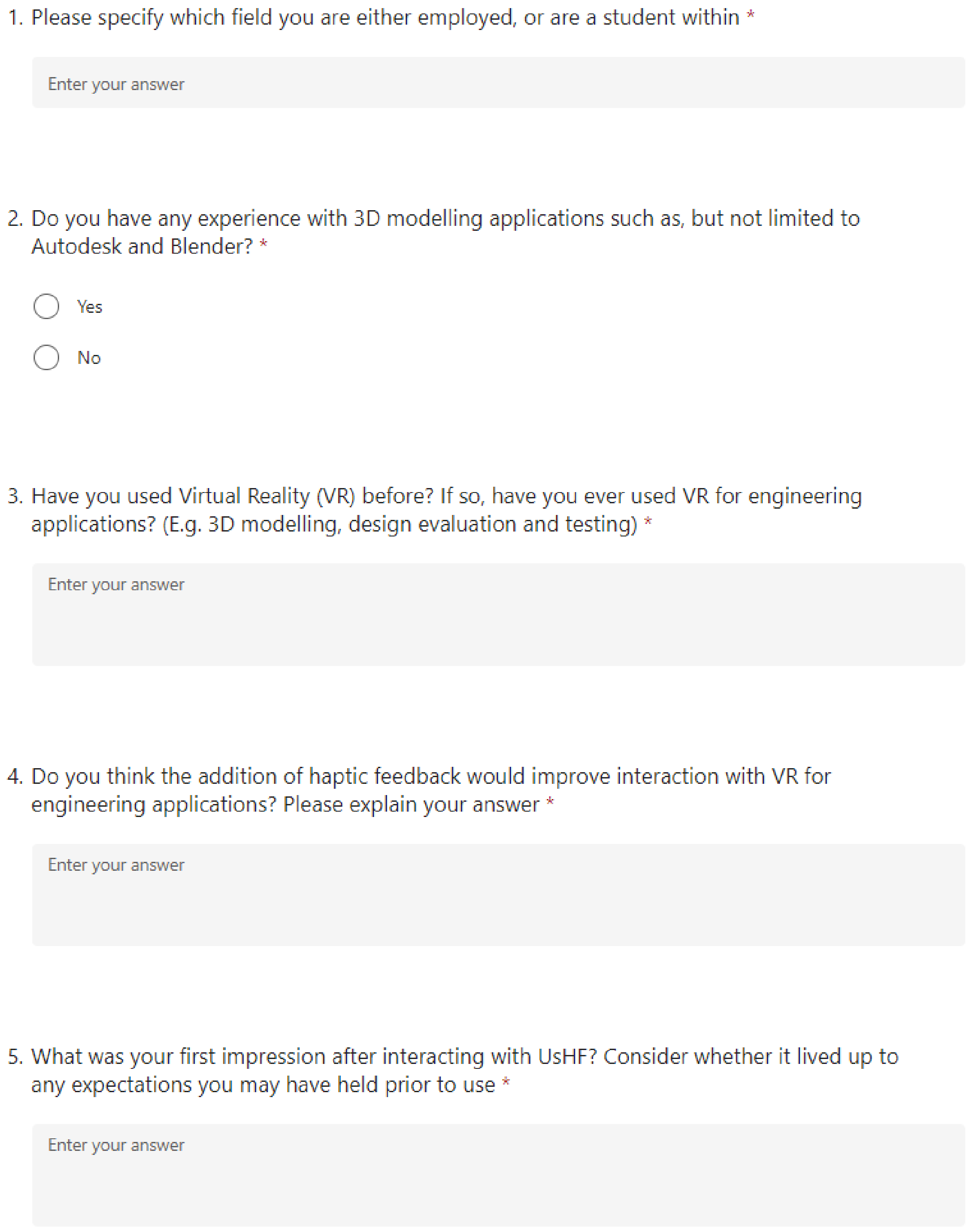
4: Answer sheet given to participants during the size discrimination task. Does not include answer fields or sheets for all conditions as these were replicated – Study 5



2. For each pair of shapes, please indicate which shape you think was LARGEST by selecting the appropriate box. If you think both shapes are the same size, place a select in the "No Difference" column

	Shape A	Shape B	No Difference
Pair 1	○	○	○
Pair 2	○	○	○
Pair 3	○	○	○
Pair 4	○	○	○
Pair 5	○	○	○
Pair 6	○	○	○
Pair 7	○	○	○
Pair 8	○	○	○
Pair 9	○	○	○
Pair 10	○	○	○
Pair 11	○	○	○
Pair 12	○	○	○
Pair 13	○	○	○
Pair 14	○	○	○
Pair 15	○	○	○
Pair 16	○	○	○
Pair 17	○	○	○
Pair 18	○	○	○
Pair 19	○	○	○
Pair 20	○	○	○

5: Questionnaire given to participants after taking part – Study 5



1. Please specify which field you are either employed, or are a student within *

Enter your answer

2. Do you have any experience with 3D modelling applications such as, but not limited to Autodesk and Blender? *

○ Yes

○ No

3. Have you used Virtual Reality (VR) before? If so, have you ever used VR for engineering applications? (E.g. 3D modelling, design evaluation and testing) *

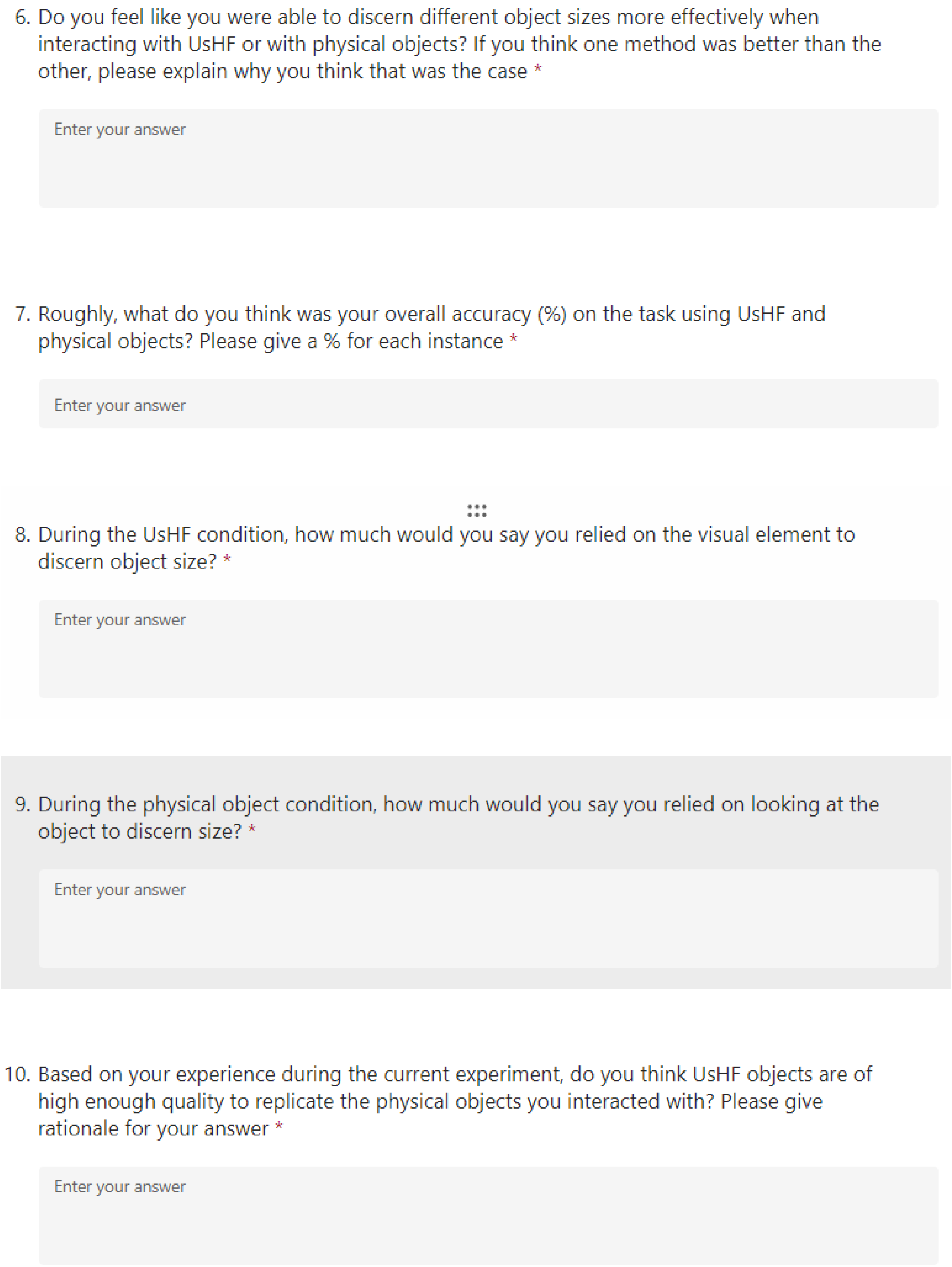
Enter your answer

4. Do you think the addition of haptic feedback would improve interaction with VR for engineering applications? Please explain your answer *

Enter your answer

5. What was your first impression after interacting with UsHF? Consider whether it lived up to any expectations you may have held prior to use *

Enter your answer



6. Do you feel like you were able to discern different object sizes more effectively when interacting with UsHF or with physical objects? If you think one method was better than the other, please explain why you think that was the case *

Enter your answer

7. Roughly, what do you think was your overall accuracy (%) on the task using UsHF and physical objects? Please give a % for each instance *

Enter your answer

8. During the UsHF condition, how much would you say you relied on the visual element to discern object size? *

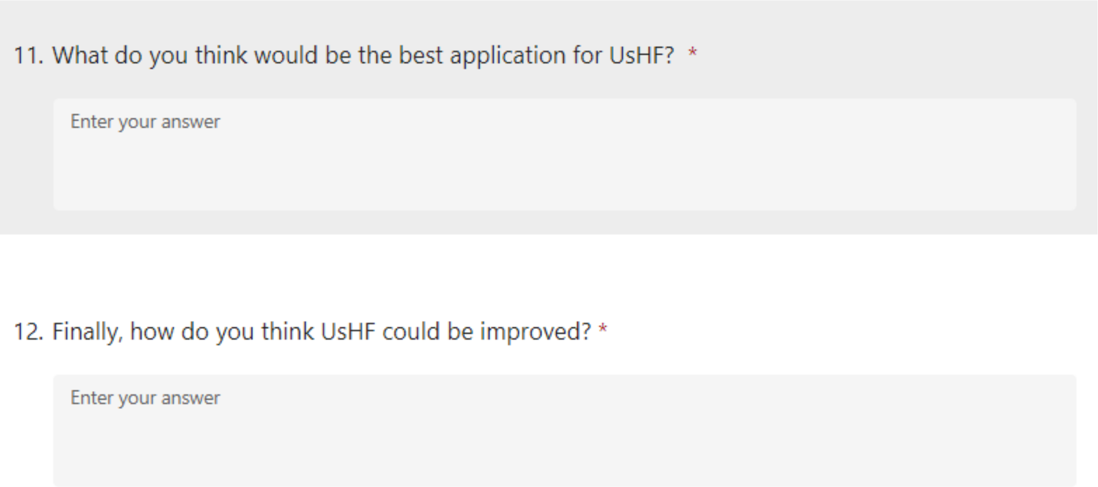
Enter your answer

9. During the physical object condition, how much would you say you relied on looking at the object to discern size? *

Enter your answer

10. Based on your experience during the current experiment, do you think UsHF objects are of high enough quality to replicate the physical objects you interacted with? Please give rationale for your answer *

Enter your answer



11. What do you think would be the best application for UsHF? *

12. Finally, how do you think UsHF could be improved? *

6: Debrief given to participants after taking part – Study 5

Participant Debrief

Thank you for participating in this study. Ultrasound Haptic Feedback (UsHF) if a relatively new technology with many potential applications. We are interested in the use of UsHF within Virtual Reality (VR) systems used for engineering design. As such, it is important to understand the processes involved in individual interpretation of haptic stimuli. More specifically, whether UsHF affords the user accurate perception of object size, as this information is critical when manipulating both physical and virtual objects.

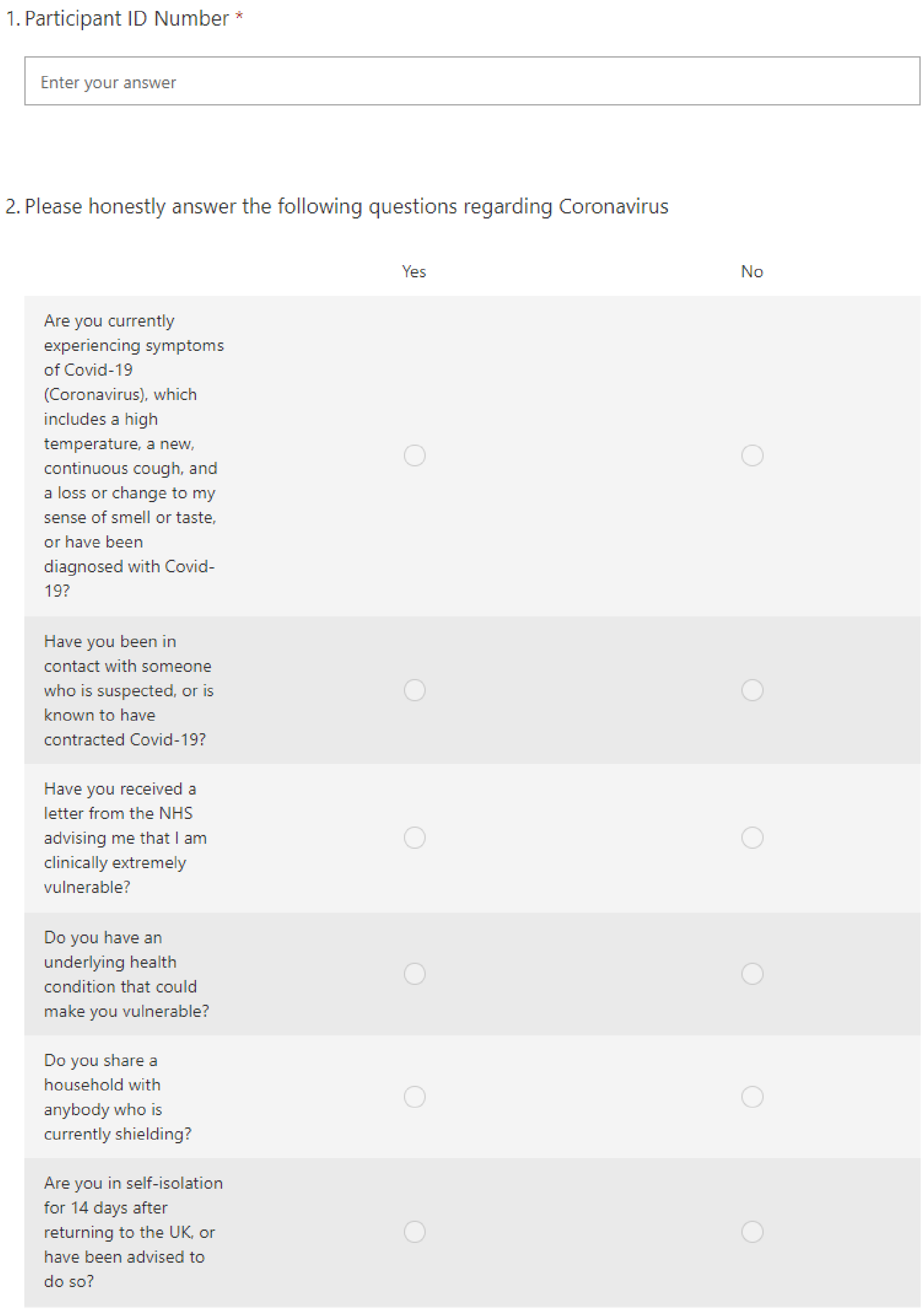
During the study you were presented with pairs of circles using UsHF and also physical versions of those objects. You then rated which shape was largest in each pair, or whether they were both the same. This task was separated into 2 conditions. In summary, the conditions were UsHF with visual feedback and physical objects. These conditions sought to establish whether UsHF provides a rendition of a shape truly analogous to its physical counterpart, and thus, whether UsHF will benefit the user in the desired application. Indeed, it is possible that UsHF cannot adequately render objects to aid their perception, this is what we hope to establish.

If you have any questions about the investigation, would like to see the results or would like to withdraw your data, please do not hesitate to contact the researcher via email at James.Khan@nottingham.ac.uk or the project supervisor, Glyn.Lawson@nottingham.ac.uk

If you have any further questions or complaints regarding ethics, please contact the Faculty of Engineering ethics committee - ez-eng-ethics@nottingham.ac.uk

Appendix F: COVID-19 Track and Trace form

1: COVID-19 Screening form used during Study 4 and 5

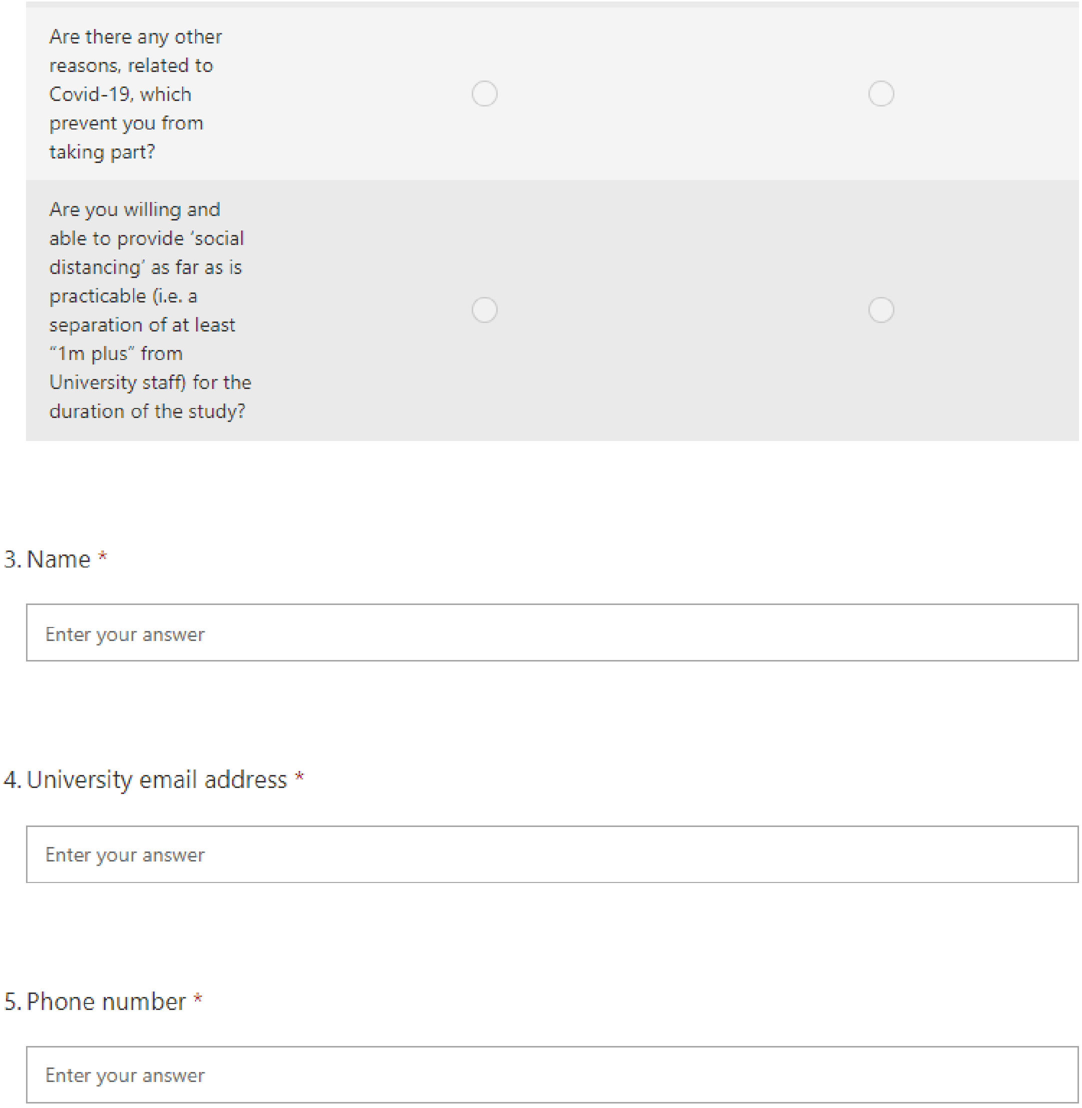


1. Participant ID Number *

Enter your answer

2. Please honestly answer the following questions regarding Coronavirus

	Yes	No
Are you currently experiencing symptoms of Covid-19 (Coronavirus), which includes a high temperature, a new, continuous cough, and a loss or change to my sense of smell or taste, or have been diagnosed with Covid-19?	○	○
Have you been in contact with someone who is suspected, or is known to have contracted Covid-19?	○	○
Have you received a letter from the NHS advising me that I am clinically extremely vulnerable?	○	○
Do you have an underlying health condition that could make you vulnerable?	○	○
Do you share a household with anybody who is currently shielding?	○	○
Are you in self-isolation for 14 days after returning to the UK, or have been advised to do so?	○	○



Are there any other reasons, related to Covid-19, which prevent you from taking part?	○	○
Are you willing and able to provide 'social distancing' as far as is practicable (i.e. a separation of at least "1m plus" from University staff) for the duration of the study?	○	○

3. Name *

Enter your answer

4. University email address *

Enter your answer

5. Phone number *

Enter your answer

Appendix G: Supplementary materials used during Study 6

1: Study brief given to participants before answering the questionnaire – Study 6

Virtual Engineering Design Questionnaire

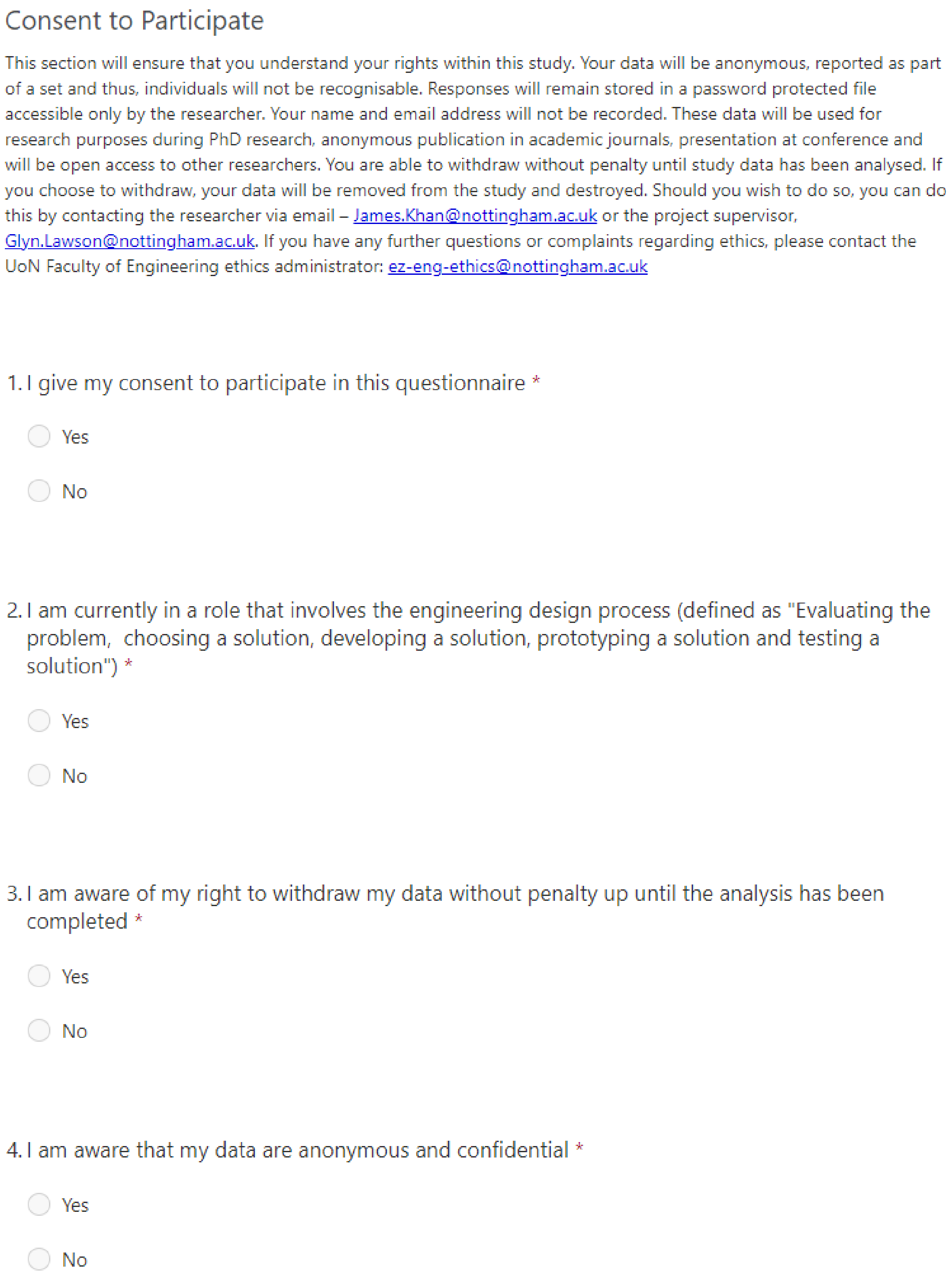
Thank you for your interest in this questionnaire. I am currently conducting my PhD research investigating multimodal/multisensory Virtual Reality (VR) for engineering applications at the University of Nottingham. As such, this questionnaire is only relevant to individuals who are part of the engineering design process, which for the purposes of this study is defined as "evaluating the problem, researching the problem, choosing a solution, developing a solution, prototyping a solution and testing a solution". No students please, only people who are based in industry. You will be asked a number of questions about your experience of current engineering design practices and will seek your feedback and suggestions of how you believe they can be improved.

This questionnaire has been given ethical approval by the University of Nottingham, Faculty of Engineering ethics committee.

Initially you will be asked to read, understand and provide ethical consent to take part in this study. After giving your consent to participate, you will be asked a series of questions on the subject of current and future engineering design processes. Please answer the questions in as much detail as possible. The questionnaire will take approximately 20 minutes to complete. Your involvement is voluntary, and you may withdraw at any point without giving a reason or being penalised. If you have any questions before taking part, please email me: James.Khan@nottingham.ac.uk

Thank you

2: Consent form given to participants before answering the questionnaire – Study 6



Consent to Participate

This section will ensure that you understand your rights within this study. Your data will be anonymous, reported as part of a set and thus, individuals will not be recognisable. Responses will remain stored in a password protected file accessible only by the researcher. Your name and email address will not be recorded. These data will be used for research purposes during PhD research, anonymous publication in academic journals, presentation at conference and will be open access to other researchers. You are able to withdraw without penalty until study data has been analysed. If you choose to withdraw, your data will be removed from the study and destroyed. Should you wish to do so, you can do this by contacting the researcher via email – James.Khan@nottingham.ac.uk or the project supervisor, Glyn.Lawson@nottingham.ac.uk. If you have any further questions or complaints regarding ethics, please contact the UoN Faculty of Engineering ethics administrator: ez-eng-ethics@nottingham.ac.uk

1. I give my consent to participate in this questionnaire *

○ Yes

○ No

2. I am currently in a role that involves the engineering design process (defined as "Evaluating the problem, choosing a solution, developing a solution, prototyping a solution and testing a solution") *

○ Yes

○ No

3. I am aware of my right to withdraw my data without penalty up until the analysis has been completed *

○ Yes

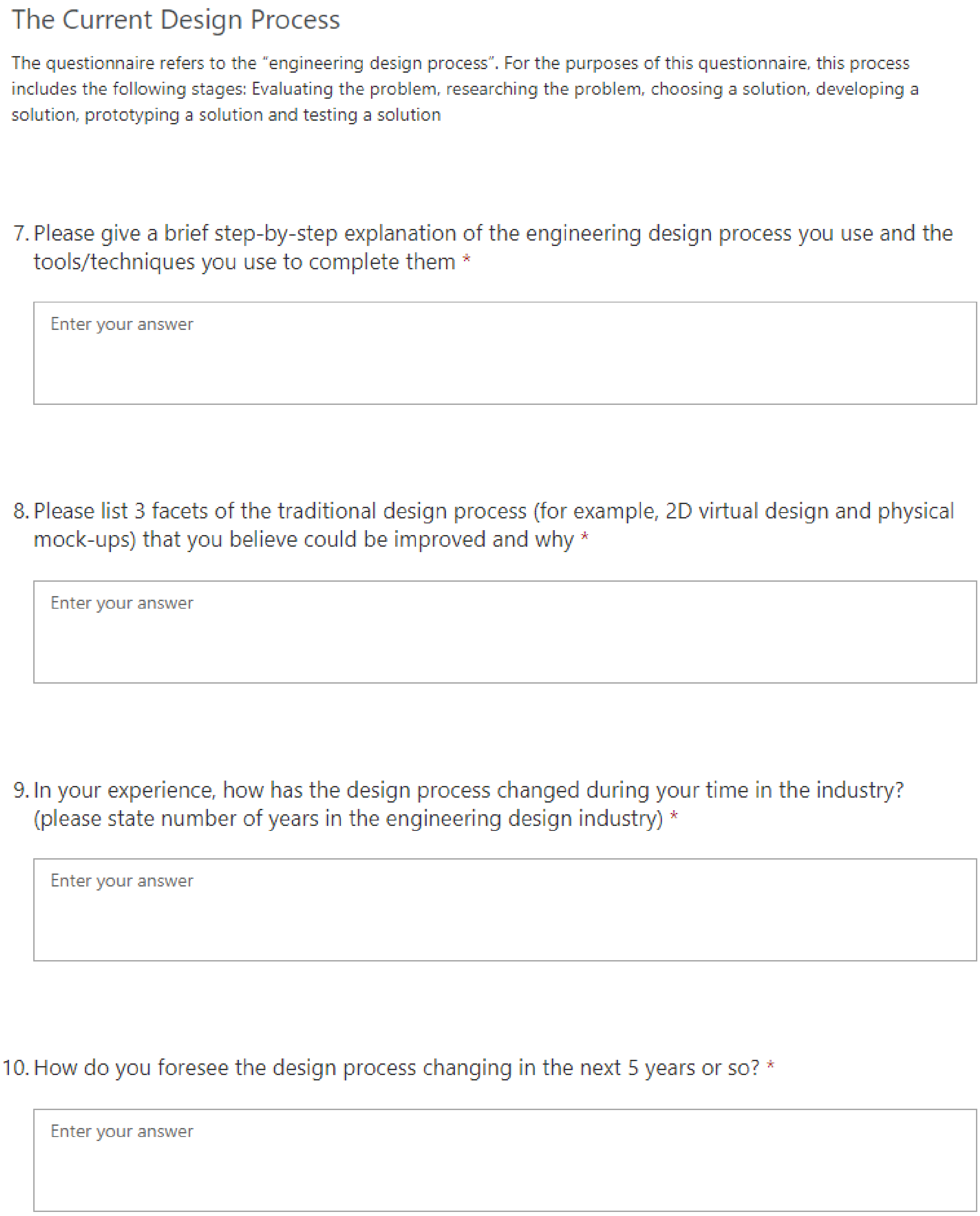
○ No

4. I am aware that my data are anonymous and confidential *

○ Yes

○ No

3: The questionnaire given to participants – Study 6



The Current Design Process

The questionnaire refers to the "engineering design process". For the purposes of this questionnaire, this process includes the following stages: Evaluating the problem, researching the problem, choosing a solution, developing a solution, prototyping a solution and testing a solution

7. Please give a brief step-by-step explanation of the engineering design process you use and the tools/techniques you use to complete them *

Enter your answer

8. Please list 3 facets of the traditional design process (for example, 2D virtual design and physical mock-ups) that you believe could be improved and why *

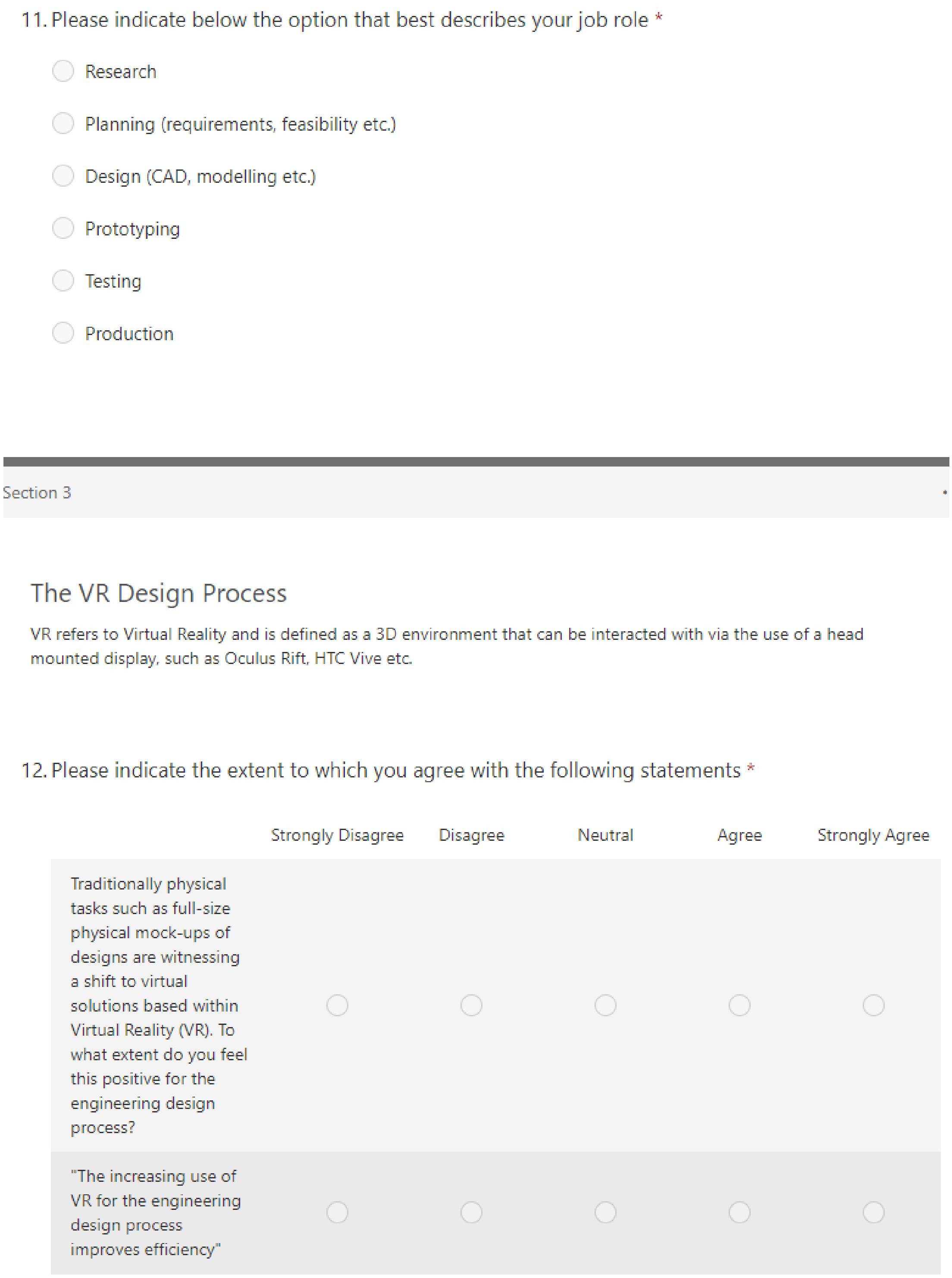
Enter your answer

9. In your experience, how has the design process changed during your time in the industry? (please state number of years in the engineering design industry) *

Enter your answer

10. How do you foresee the design process changing in the next 5 years or so? *

Enter your answer



11. Please indicate below the option that best describes your job role *

○ Research

○ Planning (requirements, feasibility etc.)

○ Design (CAD, modelling etc.)

○ Prototyping

○ Testing

○ Production

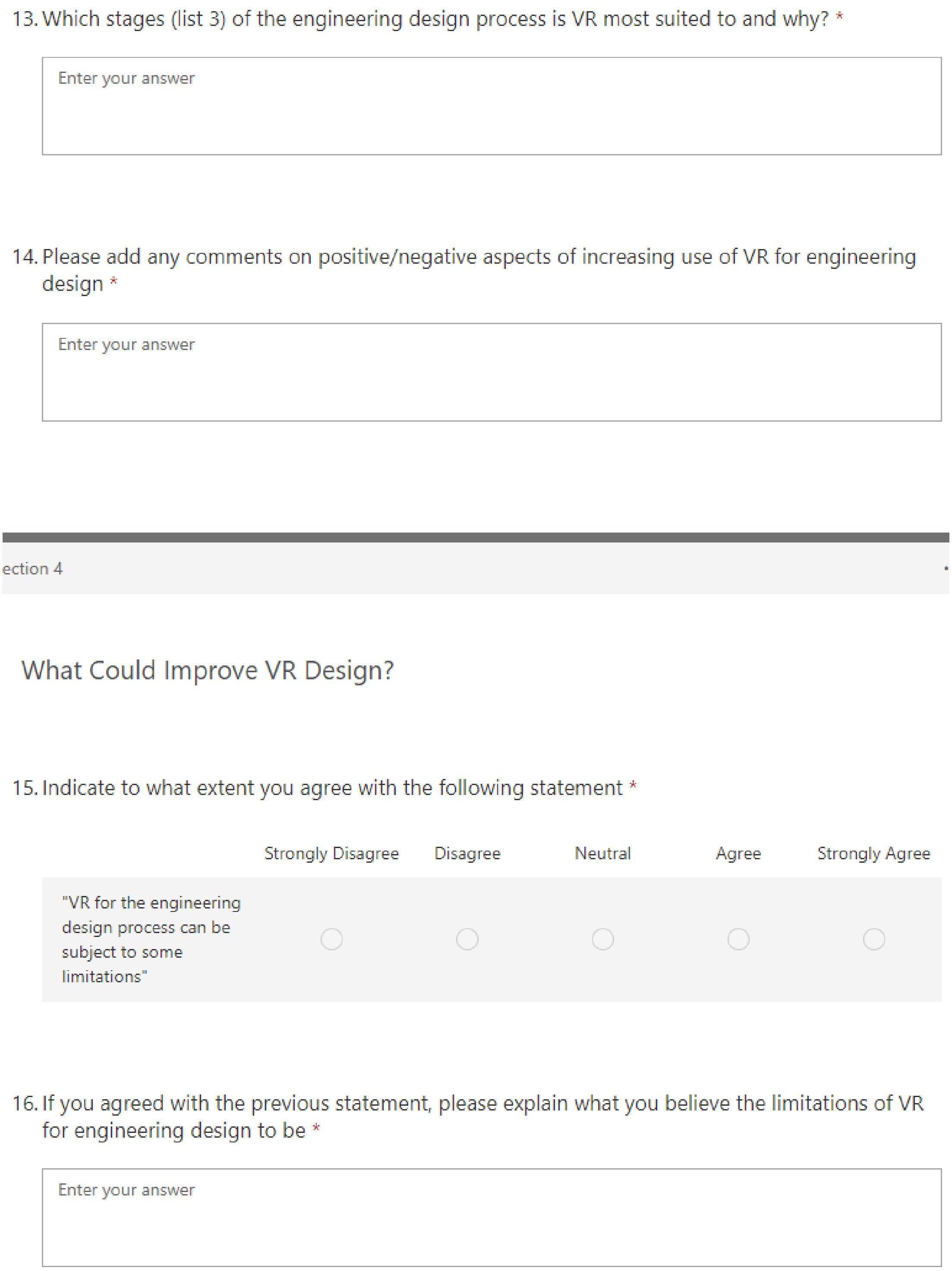
Section 3

The VR Design Process

VR refers to Virtual Reality and is defined as a 3D environment that can be interacted with via the use of a head mounted display, such as Oculus Rift, HTC Vive etc.

12. Please indicate the extent to which you agree with the following statements *

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Traditionally physical tasks such as full-size physical mock-ups of designs are witnessing a shift to virtual solutions based within Virtual Reality (VR). To what extent do you feel this positive for the engineering design process?	○	○	○	○	○
"The increasing use of VR for the engineering design process improves efficiency"	○	○	○	○	○



13. Which stages (list 3) of the engineering design process is VR most suited to and why? *

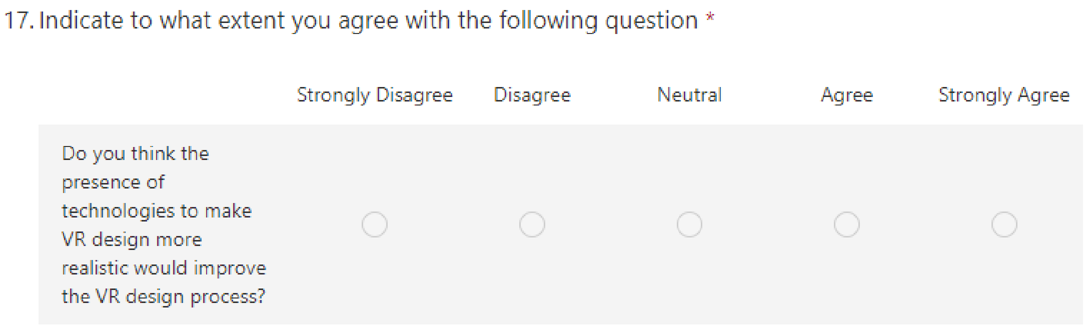
14. Please add any comments on positive/negative aspects of increasing use of VR for engineering design *

What Could Improve VR Design?

15. Indicate to what extent you agree with the following statement *

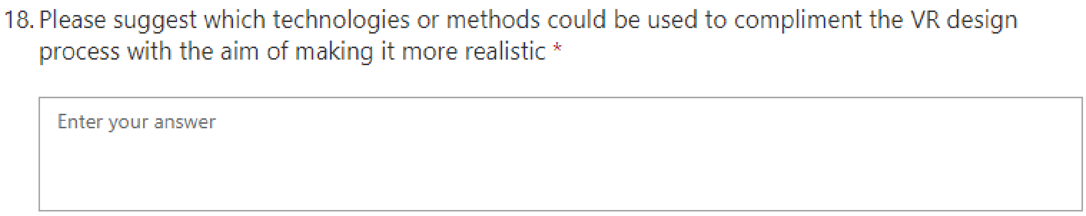
	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
"VR for the engineering design process can be subject to some limitations"	○	○	○	○	○

16. If you agreed with the previous statement, please explain what you believe the limitations of VR for engineering design to be *



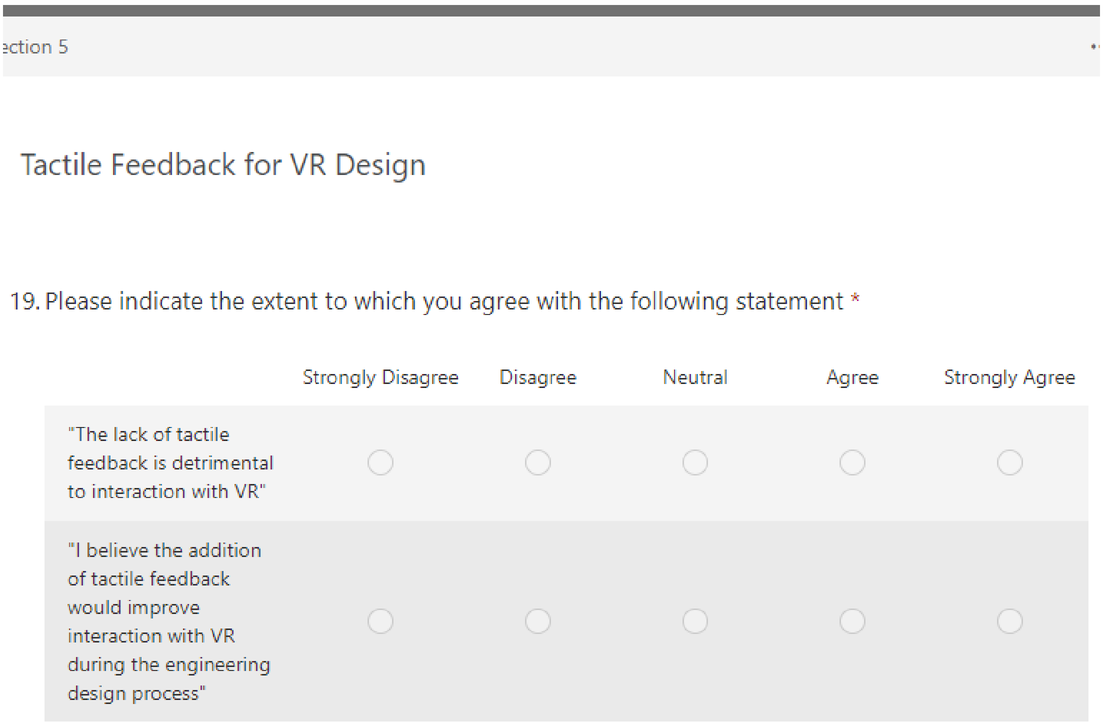
17. Indicate to what extent you agree with the following question *

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Do you think the presence of technologies to make VR design more realistic would improve the VR design process?	○	○	○	○	○



18. Please suggest which technologies or methods could be used to compliment the VR design process with the aim of making it more realistic *

Enter your answer

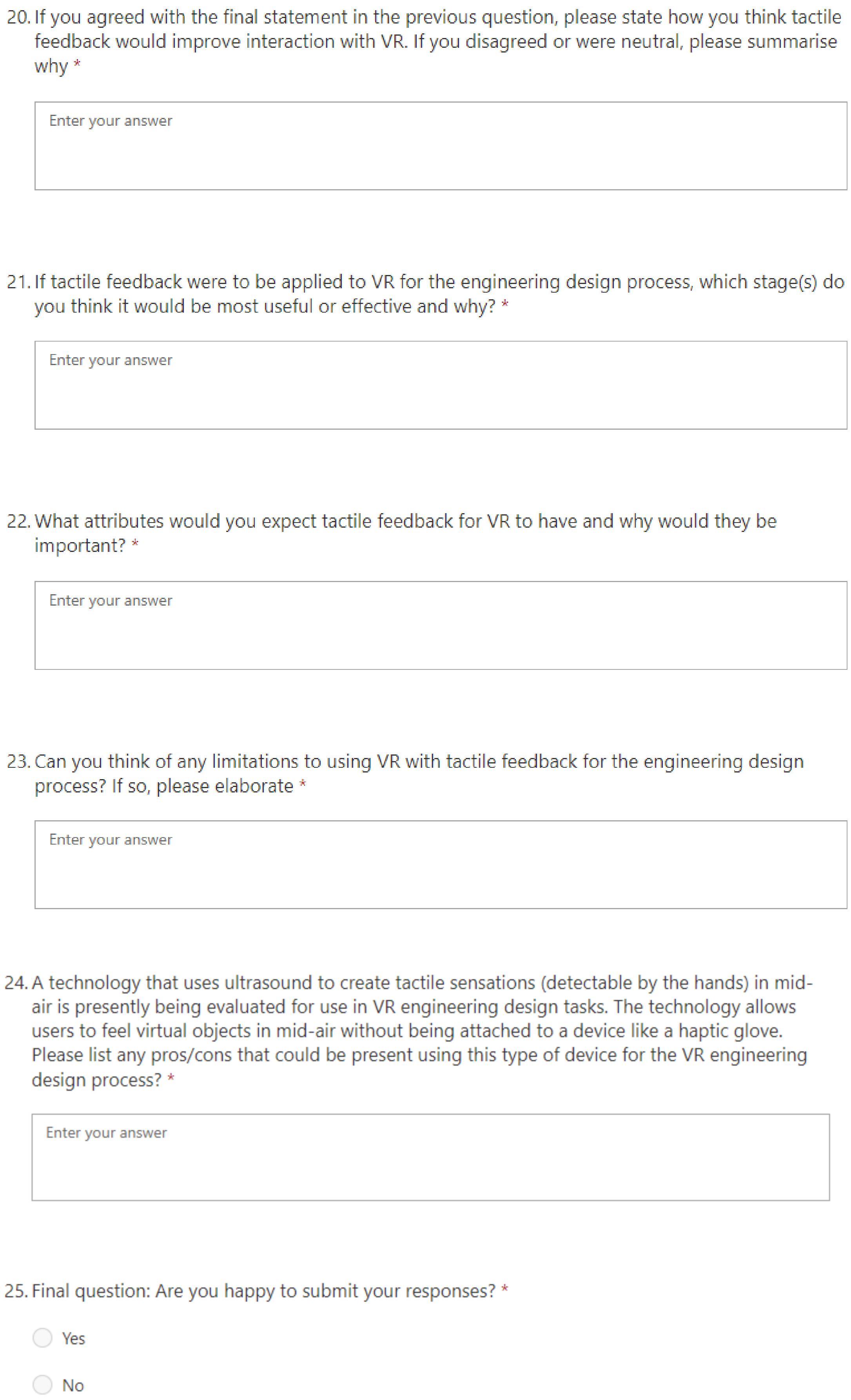


ection 5

Tactile Feedback for VR Design

19. Please indicate the extent to which you agree with the following statement *

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
"The lack of tactile feedback is detrimental to interaction with VR"	○	○	○	○	○
"I believe the addition of tactile feedback would improve interaction with VR during the engineering design process"	○	○	○	○	○



20. If you agreed with the final statement in the previous question, please state how you think tactile feedback would improve interaction with VR. If you disagreed or were neutral, please summarise why *

Enter your answer

21. If tactile feedback were to be applied to VR for the engineering design process, which stage(s) do you think it would be most useful or effective and why? *

Enter your answer

22. What attributes would you expect tactile feedback for VR to have and why would they be important? *

Enter your answer

23. Can you think of any limitations to using VR with tactile feedback for the engineering design process? If so, please elaborate *

Enter your answer

24. A technology that uses ultrasound to create tactile sensations (detectable by the hands) in mid-air is presently being evaluated for use in VR engineering design tasks. The technology allows users to feel virtual objects in mid-air without being attached to a device like a haptic glove. Please list any pros/cons that could be present using this type of device for the VR engineering design process? *

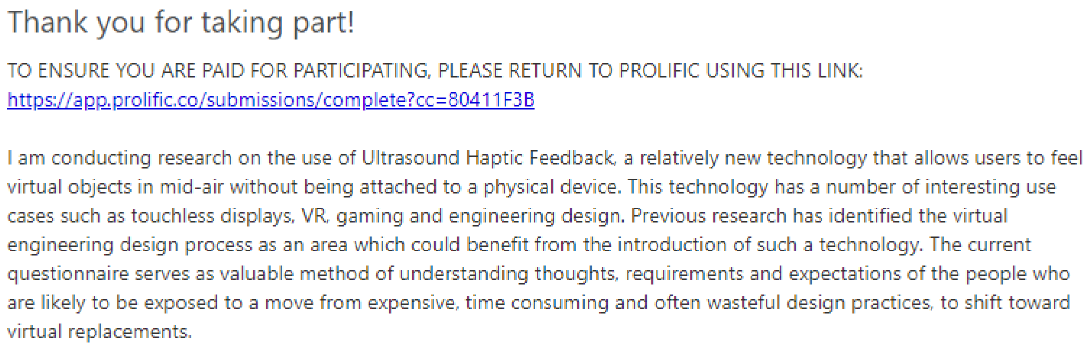
Enter your answer

25. Final question: Are you happy to submit your responses? *

○ Yes

○ No

4: Debrief given to participants after answering the questionnaire – Study 6



Thank you for taking part!

TO ENSURE YOU ARE PAID FOR PARTICIPATING, PLEASE RETURN TO PROLIFIC USING THIS LINK:
https://app.prolific.co/submissions/complete?cc=80411F3B

I am conducting research on the use of Ultrasound Haptic Feedback, a relatively new technology that allows users to feel virtual objects in mid-air without being attached to a physical device. This technology has a number of interesting use cases such as touchless displays, VR, gaming and engineering design. Previous research has identified the virtual engineering design process as an area which could benefit from the introduction of such a technology. The current questionnaire serves as valuable method of understanding thoughts, requirements and expectations of the people who are likely to be exposed to a move from expensive, time consuming and often wasteful design practices, to shift toward virtual replacements.