

# Haptic Feedback in Virtual Reality: An Investigation Into The Next Step of First Person Perspective Presence



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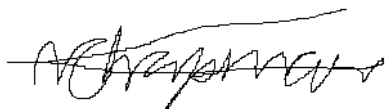
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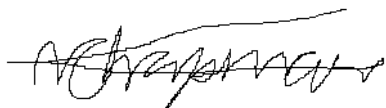


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# Abstract

Video games are becoming progressively sophisticated with new interesting mechanics and increasingly realistic graphics. Game technologies manufacturers are constantly striving to find innovative ways of providing additional layers of interactivity, and engagement with the player. In video games haptic feedback has traditionally been delivered by motors and pulleys through interfaces such as steering wheels and joysticks, or via a simple vibration mechanism in the controllers. However, while the growing popularity of commercial virtual reality technologies has provided video game developers with a new modality to introduce greater levels of immersion and presence into games, haptic technology in gaming has kept to its traditional roots.

In this thesis we investigate the impact that haptic feedback has on player presence within virtual reality environments. We introduce a non-intrusive haptic interface that can be used alongside consumer grade virtual reality technology. This thesis will demonstrate the implementation and technical considerations made during the construction of this device. We then demonstrate the systems effectiveness through a user study evaluating users reactions towards the system when compared with traditional vibration-based haptics and with the absence of any feedback, in a virtual reality game environment.

The results from this study show a positive impact on player presence when using the non-intrusive haptic device, with broken down presence scores suggesting the device was successful in delivering a satisfying haptic experience. Results also indicate an improvement in the way participants perceive their own performance when using the device, with presence scores suggesting this is due to participants being able to fully place themselves in the experience.

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# Chapter 1

## Introduction

Tactile feedback, often referred to as ‘Haptics’, defined by Dzidek as “the interdisciplinary study of how we transmit and understand information through our sense of touch” [1]. Haptic feedback in video games is traditionally delivered by one of two methods: *Force Feedback* generally uses motors and pulleys in a device (such as a steering wheel) to simulate resistance. Alternatively, *Vibration Feedback* uses various strengths and amplitudes of vibrations to simulate a variety of sensations through relatively simple algorithms and strategic placement of vibration actuators.

Creating satisfying tactile feedback in video games is a current and relevant challenge for the entertainment sector. This is due to the limited range of tactile sensations that can be simulated by currently available hardware, along with the complexity of our sense of touch. Furthermore, the devices used for the delivery of these sensations (including touch screens and physical controllers) are limited by practical and ergonomic considerations such as: cost, ease of use, form factor, weight and accessibility.

The introduction and growing popularity of commercial virtual reality technologies has provided developers with new methods of introducing increased levels of presence and interactivity. The current commercial virtual reality market is lead by two high cost mainstream headsets (*Oculus Rift* and *HTC Vive*) as well as numerous more accessible mobile headsets such as the *Samsung Gear VR*. In addition to this there is a large amount of successfully crowd funded headsets, such as the *Pimax*, proving that there is an active desire to keep virtual reality a

relevant consumer level technology. This trend is also seen in the VR peripherals market with the development of VR controller technologies, aiming to make interacting with virtual environments more compelling. An example of this is the *Manus VR* glove controllers which are currently in development, allowing unrestricted movement and individual finger tracking. An additional case is the recently released *Vive Tracker* which allows users to attach the controller to an object such as a toy gun or tennis racket, turning it into a tracked object.

Feedback in virtual reality is still implemented in the traditional vibrotactile fashion, as seen in both the *Vive's* wands' and *Oculus Touch* controllers, consequently, limiting the platform from reaching its full potential in delivering a complete sensory experience. Sales statistics show consumers being drawn towards the mobile headsets, as it is viewed that the experience of the *HTC Vive* and *Oculus Rift* does not warrant the high price point. Further concerns expressed by consumers are the large amount of space required and additional high end computer components needed for to operate VR systems [2]. These new systems and the current stagnation in commercially available force feedback technology accentuates one of the current grand challenges in the field, integrating force feedback with these systems to allow the player to "feel" the virtual world.

## 1.1 Background of Haptics in Video Games

Currently it would be unthinkable for video game hardware developers to ship devices that don't have the ability to deliver haptic feedback. Likewise for video game developers to deliver a game that does not employ this feedback in some capacity. This was not always the case, the first time haptic feedback was implemented in video games was in the form of vibrotactile feedback in 1976 on *Sega's Moto-Cross* arcade game, later re-branded as *Fonz*. The feedback allowed players to feel the rumble of the motorcycle if they crashed into another player. This came about because of the increasing pressure on arcades to provide their visitors with unique experiences, as the industry started to move towards in home

entertainment systems. It was a big success in drawing people back into arcades [3].

Over the next ten years arcade game developers began adding vibrotactile feedback into their games. In 1982 *Tatsumi* finished development on *TX-1* which was a racing game comprised of 3 screens, X/Y directional yoke and allowed players to feel the rumble of the car. This was the first use of vibrotactile feedback that drastically enhanced the driving simulator experience. Following this *Williams Electronics* released the *Earthshaker* in 1989, which was the first pinball machine that utilised vibrotactile feedback. By the late 1990's nearly all arcade games employed some form of vibrotactile or force feedback. First-person shooting games would deliver the kickback sensation from firing, whilst fighting games would deliver rumbles upon player defeats. Arcade cabinets became highly immersive machines engaging the visual, auditory and tactile modalities of perception [3].

Following the success of haptic feedback being integrated into arcade games, console manufacturers took notice and began developing ways to include the feedback in their mass market in-home systems. In 1997 *Nintendo* released the *Rumble Pak* that player's could insert into the back of a controller which would then deliver vibrotactile feedback. This feedback was achieved through the use of an offset weight attached to a DC motor. In the same year *Microsoft* released the *Sidewinder Force Feedback Pro* controller to be used with PC games, and *Sony* released the *Dualshock* controller for the *Playstation*. In 1999 the *Sega Dreamcast* was released along with two methods of delivering haptic feedback: the *Tremor Pak* and the *Sega Jump pack* [4].

The following years saw a waning interest towards video game haptic feedback technologies, until 2007 in which the *ForceWear Vest* was released. Re-branded as the *Space Vest* [5], it delivered directional haptic feedback allowing hits on the players body to be felt. In years from 2008 to present the interest in this technology has continuously increased, with research taking place concerned with development of tactile vests [6] being carried out. The release and popularisation of commercially available virtual reality technologies has sparked a new wave of device development and haptic research. These devices range from contact devices

such as gloves, suits and texture replication, to non-contact devices such as air feedback and texture replication by static electricity and ultrasonic radiation.

## 1.2 Motivation

Currently the only options virtual reality players have for fully supported controllers are wand based devices, such as: the *Oculus Touch* controllers and the standard *HTC Vive* wands. whilst these controllers have proven successful as an introductory control method for interacting with these new virtual environments, these controllers may struggle to deliver the same amount of interactivity once virtual reality applications progress past the simple point and play style. Furthermore, these control methods are potentially stunting the platforms growth, not only limiting the interactive experiences created for the platform but also the applications that it could be utilised for. Consequently, sales of the *Oculus Rift* and the *HTC Vive* suggest that players are reasonably satisfied with the current commercially available technology. In comparison the sales of the *Samsung Gear VR* and other mobile headsets, that don't have any substantial control method, are currently higher than both the *Oculus Rift* and *Vive* headsets [2]. With commercially available data gloves on the horizon the question is raised, how much do players value tactile feedback in virtual reality environments and what impact will enhanced feedback have on their overall experience?

With this popularity of commercial grade virtual reality technology it is natural that both well developed and start up companies have turned their hand towards tackling this alluring challenge. An example of such a solution are *Haptx's Haptx Gloves*, which use a number of small pneumatic actuators attached to the tips of a users fingers. These actuators push against the skin upon interacting with a virtual object in the same way handling a real object would. *Haptx's* gloves are an impressive piece of technology; however, the main issue that prevents these gloves from being practically employed for commercial level virtual reality is the chunky trail of cables attached to the gloves which are required for them to work. Consequently, when used with any fairly active virtual reality game

these cables would potentially become frustrating and intrusive when teamed with the cable also required by a VR headset. There are many more solutions in progress by various companies many of them choosing to go in the direction of wearable technologies such as gloves, vests or even full body suits. This raises the question, is the quest for improved haptics going to turn consumers away from virtual reality, due to the lack of a 'pick up and play' style?

Due to the nature of hardware development being a continuously iterative process, it is inevitable that solutions such as Haptix's gloves will be refined to a stage where commercial VR consumers will start to adopt these technologies. There are many reasons why this hasn't been solved prior to this stage, the most obvious being that before the introduction of commercially available virtual reality there was not a large requirement for it, as vibrotactile feedback was sufficient. In some respects this is also still the case with virtual reality technologies; however, now a platform that is widely accessible and has the potential for full player immersion is available, a large opportunity for innovation has emerged with it. A further challenge is that our sense of touch is an incredibly complex sense to replicate, even more so for use in video game environments where new sensations can be experienced. To replicate the sense with a single device, while still keeping the device non intrusive and non restrictive is immensely difficult and it's doubtful that such a device will exist in the imminent future that can deliver these sensations to an accuracy that would be needed. Additionally, the majority of haptic devices currently in development aim to deliver a new haptic experience but also act as a control device. Looking at this from a consumers point of view where expense is a high priority, solutions that incorporate haptics in a control method are likely to be expensive, potentiality pushing consumers away, as the initial purchase of a VR headset is already costly. This highlights an alternative way of tackling the haptic challenge as well as a key feature of our solution, by looking for ways to simulate sensations that can be used with peripherals consumers will already possess.

This thesis aims to explore the use of haptic feedback in virtual reality environments. It will identify and address the problem areas of designing and implementing haptic devices to be used alongside current commercial VR

technologies. Furthermore, this thesis will strive to introduce a non-intrusive method of delivering force feedback suitable for commercial use, as well as validating the effectiveness of this device. This system will be able to introduce players to new sensations aiding player presence and encourage the migration from exclusively using vibrotactile feedback.

## 1.3 Research Questions

This thesis seeks to answer the following research questions:

- What impact do certain object properties have on presence within a virtual reality environment? Will a users mind bridge the disconnect that is experienced, when something is physically experienced but not visually perceived?
- Can satisfying tactile feedback be created and delivered by a device that is non-intrusive and applicable for commercial virtual reality use?
- What is the impact on presence when using feedback delivered by a non-intrusive device?

## 1.4 Objectives

In order to satisfy research questions, this thesis will endeavour to:

- Conduct a review of the literature regarding tactile feedback in video games and related topics.
- Identify and analyse current tactile feedback technologies.
- Survey commercial and prototype tactile feedback devices in video games.
- Devise an experiment to explore the impact haptic feedback has on presence and the most prominent haptic modalities when used with virtual reality.
- Using results from the experiment to design and implement a tactile feedback device that would be applicable for use with virtual reality.



- Formulate an experiment that will validate the device and the impact that the sensations it delivers will have on user presence in an appropriate video game environment.
- Critically analyse and discuss the feedback device and results.

## 1.5 Thesis Structure

The structure of this thesis is detailed below:

- **Chapter 2** Reviews the related work in the haptic feedback field, covering topics such as medical, telepresence and game related haptic's along with delivery methods used. Furthermore, topics relating to virtual reality; presence and immersion are also covered. To conclude this chapter, the findings are summarised and a list of grand challenges is compiled.
- **Chapter 3** Presents the initial study of the thesis, which measures the impact that different object modalities have on presence. The chapter begins by introducing the study, then discussing the methodologies, design, implementation and results. The chapter is concluded with an in depth discussion, including how the results of this study impact the direction of the research.
- **Chapter 4** Introduces a new non-contact haptic solution for use in virtual reality environments. The chapter begins by introducing the device and the methodologies used to verify the device. This then leads to the design section in which design considerations, prototyping and reasoning for design choices are discussed. The chapter then continues to an in-depth technical implementation section of the device itself and the environment used to evaluate it. Finally, the results are presented and discussed along with a final discussion and critical evaluation of the device.
- **Chapter 5** Discusses the research as a whole drawing conclusions from this along with presenting any particularly interesting results that have emerged but was not specifically tested for, upon which other work may be based from. Finally, a discussion regarding limitations of the research and potential future work will be presented.

## 1.6 Contributions

This thesis contributes to the area of haptic feedback in the field of computer science. In particular, it offers a novel non-intrusive method of delivering force feedback that can be used with currently available commercial virtual reality technologies. Furthermore, it introduces and addresses issues in using compressed air in a haptic device, which has historically been avoided because of the high dispersion rate.

The approaches introduced in this thesis contributes to both the entertainment industry and academia as they can promote thought towards the creation and utilisation of touch sensations in the development of video games. Furthermore, it can inspire similar research in the area which may also build on the same technology introduced.

The thesis also involved the creation of an *Arduino* to *Unity* serial connection plugin tool, which was made publicly available, to ease the implementation of the haptic device. This tool gives the user the ability to easily establish a serial connection between an *Arduino* and the *Unity* game engine, as well as send and receive data to and from the *Arduino* and any components attached to it. It is hoped that this tool will lower the barrier to entry in the creation of innovative devices for interacting with games.

# Chapter 2

## Related Work

The purpose of this chapter is to review the body of works related to this thesis, identifying any insights or overlooked aspects between them as well as their limitations. This will satisfy the first objective outlined in section 1.3 - to conduct an extensive literature review to gain a greater understanding of haptic feedback, pre-existing research and its place within the video games industry. This will identify any limitations of previously explored approaches, consequently inspiring a design that takes these issues into account.

The review is carried out by first gaining an understanding of immersion and presence in video games in order to better understand practices and techniques used to measure presence. The review is continued by investigating the sense of touch and research relating to the artificial replication of sensations. Following this, the research surrounding contact and non-contact haptics is analysed. Finally, the review focuses on research using experimental and commercially available haptic devices employed in the entertainment industry, medical sector and other virtual training environments. The findings of this review are then summarised and any insights, overlooked aspects, similarities and limitations of the approaches are discussed.

### 2.1 Presence

Presence and immersion are often confused with each other and are often used interchangeably. McMahan describes immersion as a players engrossment in a

game's story and the strategy of the gameplay covering both the diegetic and non-diegetic levels. While presence is defined as how much the player believes that they are in the world. Additionally, McMahan mentions that the creation of immersion also contribute to the creation of presence [7]. These definitions for presence and immersion are well validated and widely used in games related research [8]–[10].

### **2.1.1 Presence in Video Games**

McMahan analysed several case studies highlighting the importance of immersion and presence and how it can be achieved. The findings highlighted issues with intrusive technologies, for example if a player is conscious that they are wearing specific technology to control or experience the environment then complete engagement cannot be achieved [7]. This concern of intrusive technology impacting immersion and presence is also supported by multiple studies focusing on both traditional and augmented reality, [11], [12].

Schneider et al examined the use of story narratives in first-person shooter video games. In the study they manipulated the storyline in four different video games, two with storylines and two without, measuring the effect a lack of story had on presence. Results showed that participants reported feeling stronger presence sensations and identified more with the video game characters when there was a story in the game [13].

Przybylski et al, identified that the major predictor of presence in video games is the level that the game can satisfy a players motivation to play [14]. This is supported by Ryan et al who emphasise that the game play which can satisfy the needs for competence, autonomy and relatedness robustly increase a players sense of immersion [15].

Looking into the influence of haptic feedback on presence Basdogan et al investigated the influence of haptics on co-presence, the sense of being with another person in a virtual environment. In their study, subjects would be located

at remote sites without seeing or hearing each other, they could only feel the forces that they exerted on the others hand by jointly moving a ring along a wire within the virtual environment. Results of the study showed that the visual and haptic feedback condition was associated with greater co-presence than visual feedback of the ring and wire alone [16].

### **2.1.2 Measuring Presence**

The measuring of presence in virtual environments has been a popular topic to base research on for many years, with researchers each stating their own methods for measuring and quantifying presence. Witmer et al stress that any measure of presence should be both reliable (only depending on the characteristics under consideration) and valid (measuring what it intends to measure accurately) [17].

There is a large number of well validated presence questionnaires. A questionnaire developed over a number of studies by Slater et al has been widely used in presence related research [18]. The questionnaire is based on three themes: the sense of “being there”; the extent that the virtual environment becomes more “real/present” than everyday reality and the extent to which the environment is thought of as a place was visited [19].

Witmer and Singer’s presence questionnaire is another well validated and widely used questionnaire used in virtual environment presence related research. The questionnaire is based on their theory of involvement and immersion as well as previous theoretical research. They determined several factors that are thought to contribute to a sense of presence: control factors (the amount of control the user had on events); sensory factors (the quality, number and consistency of displays); distraction factors (the degree of realism portrayed) [17].

Some presence questionnaires combine and build on others that have been validated and widely used in research. An example of one of these presence questionnaires is the group presence questionnaire (IPQ). Schubert et al built the IPQ by combining Witmer and singer’s along with Slater et al’s published questionnaires with a

questionnaire from earlier research along with some newly developed questions on technological and context variables. The presence factors that entailed only subjective reports of how users experienced the virtual environment were: spatial presence (the relation between the virtual environment as a space and the own body); involvement (the awareness devoted to the environment) and realness (the sense of reality within the context of the environment) [20].

## 2.2 Immersion in Video Games

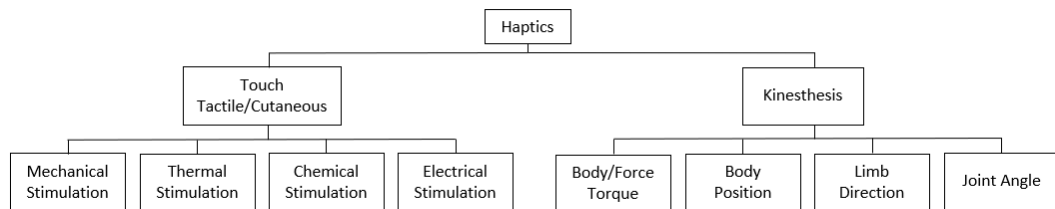
Immersion is not always a term only reserved for video games as it has been found something similar to immersion can be experienced while reading or watching movies [21]. To further this the level of immersion is very much reliant on the absorption personality trait [22]. Obviously the main difference between immersion in video games and immersion in reading or movies is that in video games the player has agency in the world which generates the players experience, where as in books and movies a scripted narrative is gradually unfolded to be consumed [23], [24]. Drawing from multiple qualitative studies Calleja [23] argues that immersion is simply one aspect of the gaming experience and proposes the concept of incorporation. With this concept a player is able to incorporate the game environment into their consciousness and at the same time be incorporated into the environment as an avatar. Immersion is then but a single aspect of incorporation teamed with the sense of transportation or presence.

Ermi and Mäyrä [25] divided immersion up into three sections: sensory, challenge-based and imaginative. Sensory immersion is easy to identify as it relates to the audiovisual aspect of video games and can be intensified though things such as more compelling graphics or playing using surround sound speakers. Imaginative immersion is based on the players absorption in the games narrative or identification with a character. However there is a concern that imaginative immersion may be a mix of both imaginative and sensory immersion. Imaginative immersion is commonly found to be most prominent in role playing games.

Challenge based immersion is gameplay experience of a player balancing their abilities against the challenges of the game, relating to motor and mental skills.

## 2.3 Sense of Touch and Haptics

In a paper on haptic interaction, Brooks defines haptics as “pertaining to sensations such as touch, temperature, pressure, etc. mediated by skin, muscle tendon or joint.” [26]. This is one of many efforts that has been made to define a terminology for haptics [27], [28]. In many cases when coming to define haptic feedback the difference between haptic and tactile feedback are often overlooked [29]. This leads to many researchers using the term haptic to include all haptic sensations and tactile in reference to the active stimulation of the skin. Erp et al [29] present a diagram (shown in Figure 1) that summarises haptics showing relationships between the components. Using this diagram the term haptics is comprised of two subgroups: tactile referring to the application of touch and kinesthesia which is the knowledge of where your limbs are in relation to your body as a way of interaction with the immediate environment.



**Figure 2.1:** The components of haptics. Touch includes stimuli such as mechanical, thermal, chemical and electrical. The “Kinaesthetic” sense is matched by kinaesthetic activity where the user exerts force on an object [29].

Coles explains that force feedback requires forces and torques to be experienced which requires 6 degrees of force feedback. However, because of high manufacturing costs force feedback and torque are rarely delivered together [30]. The survey also highlights that tactile feedback can be conveyed through varying degrees of vibrations. Suggesting the research in this thesis could incorporate a low fidelity vibration system to investigate a participants reaction to force feedback when interacting with objects within a virtual reality environment. This is supported

by Orozco, who presents an overview haptic feedback explaining the early use of video game controller vibrations. The paper also mentions steering wheel peripherals that use resistance feedback, to more recent uses in haptic jackets that simulate the force of a bullet or punch [31].

Hayward et al, highlights that the haptic field is multidisciplinary by nature, borrowing from many other areas such as robotics, psychology, computer science and biology [32]. The paper mentions the difference between inanimate or animate objects and the type of energy that these objects can pass in terms of touch sensations. Inanimate objects can only dissipate mechanical energy which active objects should supply energy, creating two categories of haptic devices termed passive or active it is emphasised that active devices should be used to replicate synthetic environments [33], [34].

### **2.3.1 Psychological and Physiological Aspects of Touch**

To effectively develop a haptic device to be used for entertainment purposes and with the desire to achieve a certain level of user experience, it is necessary to understand both the psychological and physiological aspects of touch interactions.

When looking at the Psychological aspects of touch it needs to be considered that to touch something is an intentional, socially invasive and committing act. When reaching out to touch something a person may obtain information, expose themselves to pleasure or potentially danger. Emphasised by Maclean, humans tend to be more cautious when touching compared to just looking. Designers must be aware of this particularly when creating a haptic device for virtual reality where the player may be encouraged to touch a visually undesirable object. Maclean also discusses the importance of making use of users experiences so as to use their preconceptions of what the interaction may be like, this is also supported by Classen [35], [36].

Regarding the physiological aspects of touch, the sense of touch is described as sensation gained through non-painful stimuli against the skin. The complex



system that creates our sense of touch is comprised of a large amount of differing receptors in joints, muscles and skin, each one with its own characteristics which responds to different stimuli [37].

Tactile sensing or tactile perception is the terminology used to describe a more generic sense of touch. Tactile perception accounts for small forces that are provided by a gentle touch or surface movement which allows humans to feel smooth or rough textures [38]. This type of perception is a result of multiple events when stimuli such as vibration, heat or pressure is applied to the skin. Specialised receptors will respond to this stimuli depending on the magnitude, location and type of stimuli [39]. Hairless parts of the skin such as our finger tips and palms are the most active in terms of tactile sensing as these particular areas hold a high density of the specialised receptors for sensing the components of touch. These receptors are able to detect mechanical input, when the skin is deformed, or vibrations caused by significant or minute movement [38].

### **2.3.2 Intermodal Sense of Touch**

Oakley et al highlights that tactile perception is not independent of vision and that vision may be better in negotiating perception rather than touch when both are available [28]. Furthermore, one sense will completely override the other when processing information about the same experience. In their paper Warren and Rossano state that vision and touch are both suited for different situations and will act differently depending on the nature of the perceptual performance at that time [40]. This emphasises that the two senses may work against each other or compliment each other depending on the situation.

As found by both Manyam and Heller, information coming from multiple modalities that are describing the same event is better than using a single modality for sensing surface properties. Manyam reported that people could easily judge shapes more accurately with both vision and touch [41]. Heller also found that people were more accurate in judging surface texture when both modalities were available [42].

Early work by Yoshida et al discovered that the main dimensions of haptic textures were hard-soft, heavy-light, cold-warm and rough-smooth [43]. In addition to this Hollins et al identified by using bipolar adjective scales that smooth-rough and soft-hard as the main dimensions in the perceptual space [44]. These object dimensions have held in research with multiple studies continuing to use them to carry out their haptic based research [45], [46].

### 2.3.3 Haptic Illusions

Lecuyer discusses the pseudo haptic phenomenon of haptic illusions, which is the simulation of force feedback using other sensory modalities such as vision or audio [47]. Dominjon et al, researched into simulating the mass of a virtual object. It was noticed in a study using a *Phantom Omni* device and differently weighted virtual balls that the more amplified the motion made to move the ball the lighter the ball was perceived to be. It was also reported that this was true for the reverse, when participants interacted with the lighter of the balls but the movement required was less amplified the ball was perceived as heavier. They repeated this study with the exception of gravity only using the phantom to simulate inertia of the ball. The same results were shown with the heavier ball being perceived lighter and the lighter ball heavier [48].

Supporting Dominjon et al's study, Kumar et al, investigates the simulation of pseudo stiffness of a virtual spring using a computer mouse as an input device. They used a display to deliver visual feedback which would emphasise the stiffness of the spring according the mouse button being depressed. Concluding that there was a difference in the perceived stiffness of the spring with 1 DOF(Degree of Freedom) [49].

## 2.4 Contact and Non-Contact Haptic Feedback

### 2.4.1 Contact Haptic Feedback

Interacting with objects with bare hands or through a tool can change on how accurately the object can be identified and the entire perception of a sensation through the medium it is interacted with. Lamotte emphasises that texture perception when using a tool or object to interact with a texture varies along the hard-soft dimensions. However, it is better when discriminating the differences in softness if they executed an active tapping technique when using a tool [50]. Hollins found that textural perception mainly varies along the rough-smooth dimensions [51], a finding that is also supported by Klatzky et al [52]. Hassan and Jeon investigated the difference between using bare hands and tools to interact with textures. They carried out an experiment in which participants felt a total of 31 different textures with their bare hands and a tool. They discussed that the feeling of surfaces with their hands is very familiar to them so they need less time to identify them because the range of information perceived in bare hand interaction was very wide so judging was easier and quicker. They mentioned sandpaper and rough textures were easily identifiable with both tool and bare hands where as cloth and smooth textures were not [53].

A study built on a fingertip device concept introduced by Prattichizzo et al [54] was carried out by Leonardis et al. The study aimed to minimise the encumbrance and interference that the device had with other fingers. In addition they aimed to replicate forces by stretching the skin with three DOF (degrees of freedom). The device used three electro magnetic motors to position a point under the users fingertip. Participants were required to grab and hold an object with the haptic feedback and without, only using visual information. Their results showed that without the feedback their force of grasping increased and with the feedback it returned to a natural expected grasping force increasing their control [55]. Bianchi et al also created a contact haptic device designed to be worn on the finger. The device was used to simulate softness which was an object characteristic that

Bianchi claims a lot of haptic device creators ignored. The device was constructed using multiple DC motors and a servo motor which moved and altered the tension of a stretchable fabric which had contact with the user's skin. The DC motors allowed the fabric to move which simulated slipping. The paper concluded that the device could satisfactorily simulate the softness and provide slipping cues [56].

A large portion of contact haptic devices involve using vibrotactile feedback devices. The device presented by Traylor and Tan used vibrotactile feedback in a device designed to be placed on the user's back to provide directional information [57]. A device designed for a similar purpose by Lieberman and Breazeal comprised of eight vibration actuators with individually controlled frequencies. The actuators were attached to the user's arm by a five DOF suit and would activate to guide the user's movements [58].

Prattichizzo et al. discussed the limiting nature of vibrotactile feedback as it could only create surface sensations and not realistic force that deforms the surface of the skin. Their alternative to vibrotactile feedback was a wearable contact haptic device which was worn on the finger with three DOF. The device used three motors attached to a platform via three strings. These motors altered the tension of the strings resulting in the platform deforming the skin in different ways rendering cutaneous forces [54]. The effectiveness and basic concept of this device was well validated with multiple studies creating their own iterations of the device to use in their own research [59]–[61].

Israr and Poupyrev investigate the creation of a tactile brush algorithm and apparatus that can create a convincing general purpose “tactile stroke” on the skin of participants. They aimed to create a general purpose haptic solution to mimic a moving sensation across a user's skin. To achieve this, a number of vibrating actuators were used to produce strokes on the skin making the device very diverse and capable of being applied to all parts of the body. [62]. Békésy discovered the phantom sensation, which is the phenomenon when two actuators are triggered simultaneously. A phantom sensation will be created giving the same stimulation as a third actuator located between the two. However, this phantom

sensation is always static between the two actuators and would not be able to create perceived motion [63]. Gescheider explains that the placement of the phantom actuator relies on the relative intensity of both the physical actuators, for example if both intensities were equal the phantom actuator would appear in the middle point between the two. In order to highlight the diversity of the algorithm and apparatus created. The algorithm was used to simulate sensations felt in a combat driving game, for example the sensation of an explosion pushing a car [64].

An example of a contact haptic device not using vibrotactile was developed by Li et al. The device is a texture display made with glass and two columns of piezoelectric ceramic, which works on the principle of the squeeze film effect. This is when one plate is vibrating and the other is static, the air pressure between the two is higher than standard atmospheric pressure [65]. The device was shown to be able to simulate friction change and as it is constructed of transparent glass it could be integrated with consumer electronics [66].

Gallacher et al, aimed to create an open source affordable haptic display making haptics more accessible. They named it *Haptlet*, the device is based on an *Arduino Due* much like the finger tip devices previously mentioned. It utilises two motors to position a focus point which houses a vibrotactile actuator. The device can be clipped onto a tablet or computer screen to make it universal and less intrusive than other tactile display methods whilst still remaining cost effective [67].

## 2.4.2 Non-Contact Haptic Feedback

The majority of commercially available applications of haptic feedback devices have utilised only vibrotactile or electrostatic methods; however, a number of different studies looked into the potential of using air. Gupta et al, explored non-contact haptics using air vortex rings created by using a speaker as a flexible membrane to propel air towards the user. Through using air in this way it was found that it could be targeted and controlled much easier. In the study, participants were placed 2.5m away from the device and the majority of participants responded

to haptic feedback being felt. However, a key disadvantage of using air is the dissipation rate over distance, this made accurately hitting a desired position extremely difficult depending on the targets distance from the device. In the discussion section of the paper it is mentioned that creating a range of differing sensations using air is highly unlikely, unless a participants mind also contributes to the sensation depending on what is visually being perceived [68].

Arafsha et al's, survey explores non-contact haptics to great depths, discussing both air-jet and ultrasonic radiation techniques. They highlighted the advantage of being able to experience sensations with bare hands when using air jet haptics and the high potential use in the future with video games. Table 2.2 compares the two methods: air-jet and ultrasound haptics. The air-jet method is shown as a simpler design and is capable of reaching longer distances. To conclude the survey they emphasised that the use of either of these non-contact technologies largely depends on the application. The bulky nature of air haptics and slow transfer through air limit its use in space saving and high accuracy conditions. On the other hand ultrasound is more compact and can accurately target focus points but has a very short travel distance, unwanted noise and safety concerns [69].

	<b>Air-jet</b>	<b>Ultrasound</b>
<b>Advantages</b>	<ul style="list-style-type: none"> <li>• Easy to implement</li> <li>• Long travel distances</li> </ul>	<ul style="list-style-type: none"> <li>• Small size</li> <li>• High spatial accuracy</li> </ul>
<b>Disadvantages</b>	<ul style="list-style-type: none"> <li>• Bulky</li> <li>• Low spatial resolution</li> <li>• Slower transfer through medium</li> </ul>	<ul style="list-style-type: none"> <li>• Noise</li> <li>• Short travel distance</li> </ul>
<b>Power Consumption</b>	<ul style="list-style-type: none"> <li>• Very low in most cases (control signals only)</li> </ul>	<ul style="list-style-type: none"> <li>• Relatively high (typical 40W)</li> </ul>

**Figure 2.2:** Non-contact haptic technology comparison [69].

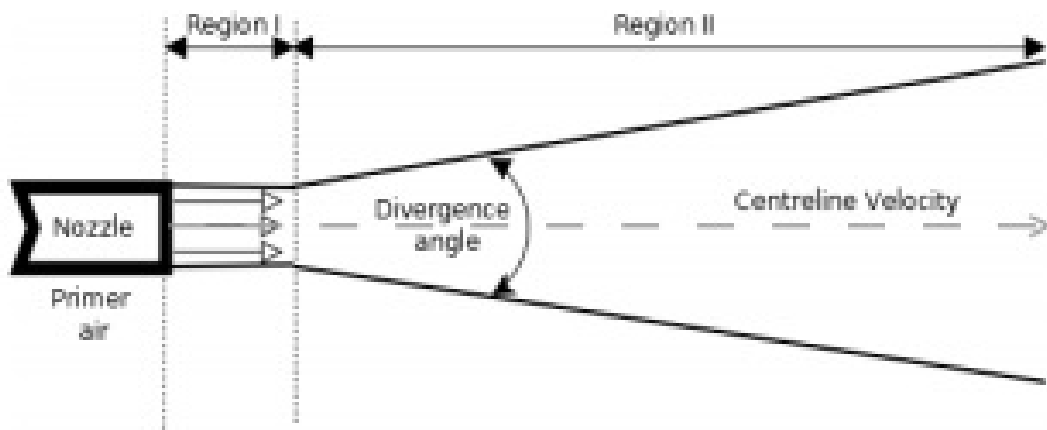
Disney developed a working 3D printed air vortex device, called *AIREAL*. During testing they used projectors to display virtual images onto the skin of participants to relate to the sensation being created by the *AIREAL*. In a technical paper on the *AIREAL* a butterfly example is used, the butterfly is projected onto the participants hand and the *AIREAL* device is used to mimic the sensation of the butterflies wings and movements on the hand. An interesting aspect of this paper

is the mention of vortex latency. This is the time between when the user would expect to feel a sensation and when the vortex delivers that sensation. This had to be calculated in order to send vortices at the correct moment so that the user can experience the sensation when expected. A further aspect researched in this paper related to the use of haptics with gesture control, much like how free hand virtual reality controls would be used. For this gesture control they tried to simulate a button press, to which participants responded that it felt like a burst of air hitting their hand. The varying textures that could be felt was also tested, it was reported that the two spectrum's that could be actually felt were smooth and pronounced bumpiness. A disadvantage of the *AIREAL* emphasised in the paper is that to achieve the majority of these sensations, multiple *AIREAL* units need to be mounted around the user which is cumbersome and limits the potential adoption from a commercial market to be used in everyday environments [70].

Suzuki and Kobayashi, first introduced a force feedback display which used air jets in a prototype that used an air compressor connected to a 10x10 grid of nozzles embedded on the surface of a table. Each nozzle was controlled by an electric valve and would only fire one at a time. Additionally, each nozzle had access to the same amount of pressure but only one nozzle would utilise it all at a time. The device was used on a virtual reality system with force feedback in which the user would hold a paddle like receiver whose position would be monitored by the system. When the user placed the paddle over a virtual object the corresponding nozzle would fire hitting the paddle and cause the user to feel the push back from the force created against the paddle [71].

Tsalamlal et al, carried out an experiment using air jet tactile stimulation on a users bare hands. The sensations were delivered by an air jet diffusion nozzle supplied by an air compressor. The aim of the study was to determine the absolute threshold (the minimum detectable intensity) and the point at which the difference was noticeable. The nozzle was placed 350mm from the users palm and they tested 25 variations of pressure intensities. The study resulted in a module function to control haptic rendering and a calculation for airflow rate [72]. Hoshi mentions that due to the physical properties of air, air jet methods lack spatial and temporal qualities that would be necessary for multimedia applications [73].

Gauntner emphasises the asymmetric free jet flow can be divided into two regions with different physical features as shown in figure 2.3. Region one corresponds to a short zone where the velocity remains constant and equal at the nozzle exit. The second region corresponds to a large region where the flow is established. It is characterised by a linear dissipation of the centre line velocity according to the distance to the outlet [74]. Tsalamlal et al, mentions that region 1 is more desirable as region 2 may not be suitable for certain applications due to the dispersion rate [72].



**Figure 2.3:** Non-contact haptics air characteristics [74]

Tsalamlal et al's paper goes on to discuss the psychophysical aspects of air jet based tactile simulation. They mentioned the downside of devices requiring contact with the user to provide feedback, additionally these devices do not satisfy the entire hand. Furthermore, most systems are intrusive and not practical in many fields such as games and desktop applications. They judged the use of acoustic radiation as not a promising method of haptic delivery as it did not allow for high intensities and could present safety risks for the user. It was discussed that air jet haptics were the most promising but the workspace in research is limited due to the deliverable distance of air. They conducted a study of 12 participants in which subjects hands were placed in front of an air nozzle and different stimuli altered by air intensity and pulses were applied. In a second study they used 15 participants much like the first they were asked to keep their hands in front of an air nozzle, this time at a fixed distance. They received the air stimuli altered by air intensity which would be increased or decreased depending



on participant's response. They concluded with an absolute threshold of air flow rate to be used on the palm of the hand and observed a relationship between the flow rate and the perceived stimuli [72].

As mentioned previously non-contact haptics can be produced through the use of ultrasound, based on the principle explored by Takahashi and Shinoda known as acoustic radiation force [75]. The principle is exploited by using electronic ultrasound transducers which can be digitally controlled with a high voltage to produce ultrasonic waves that reflect on the skin [76]. Iwamoto et al discussed their first prototype of an airborne ultrasonic tactile display designed to provide tactile feedback. Their implementation does not require the user to wear anything specific. The display radiated airborne ultrasound which exerted pressure directly onto the users skin. They state approximately 99.9 % of the energy is reflected on the users skin so they were not required to wear protective gloves. The prototype was built of 91 ultrasonic transducers arranged in a hexagon. The total force that the prototype could exert with an input amplitude of 15V was measured to be 0.8gf (gram-force) at a 250mm distance [77], [78].

Iwamoto's work was improved on by Hoshi et al, by developing a holographic system that used tactile feedback. This system consisted of a holographic display a hand tracker and the tactile display. They aimed to increase the pressure of haptic feedback provided in their previous research. They combined 4 ultrasonic transducer arrays arranging them so that they met at a focal point explaining how the different pulse widths and input voltages effected the perceived feedback [79].

Hoshi's work was continued with research investigating the creation of a non contact haptic feedback system for mid-air displays using airborne ultrasound. To achieve this a large number of ultrasonic transducers are placed in an array which emit a frequency, altering the radiation pressure allowing the simulation of different sensations. During the testing of the system participants reported being able to feel feedback in multiple targeted positions. This indicated that it was possible to specifically target an area with free air haptics. A particular interesting aspect of this study was that without the use of a display and simply using the system to simulate tactile feedback, participants reported it feeling like

electrostimulation, and "a stream of air". In contrast to this when a display was used, in this case images were projected onto participants, it was reported that they could feel the bouncing of a ball, rain drops and a small creature walking on their hand [80].

Recently a number of research studies have emerged which utilise lasers to produce non-contact sensations [81], [82]. Lee et al, explored the use of laser methods to create haptic sensations. In their studies they used a laser device designed to focus on an elastic medium attached to a users body. They monitored the tactile stimuli created from the laser by using a force sensor. By altering the amplitude and pulses of the laser they could create force that was perceived as pulling of the skin. They used 12 participants that were positioned in front of a computer and placed their finger in a stand, multiple electrical, mechanical and laser stimulus were then applied. They resulted in the laser being able to create stimuli similar to short 5ms vibrations [83].

Cha et al, carried out a study creating a mid air tactile display designed to provide continuous moving sensations along a contour of the skin. In this study they used the system they called *laser stroke* which could essentially draw sensations on the users hand. They used a Q-switched laser device which can generate 45MJ of energy for a single pulse or repeated pulses at a rate of 25HZ. They mounted the laser on a gimbal with 3 DOF in order to control the direction. They used 10 participants which were presented with two laser stimuli. The participant would place their hand on a stand and the laser stimuli would be delivered to points on their hand at which the participant would identify the stimulus and position. They concluded with the laser being able to adequately perform as a mid air tactile display [84].

## 2.5 Haptic Feedback

### 2.5.1 Haptics in the Medical Field

A large amount of haptic feedback research lies within the medical training and psychological treatment fields [85], [86]. Meijden investigated the use of haptic feedback for surgery training simulations. It is mentioned that while multiple studies support the use of haptic feedback systems a large amount work is required for accurate representation of the complex feedback given through instruments during surgery, requiring an immense amount of data collection [87]. This is also supported by Coles, who also explained that the modelling and behaviour of real tissue is too complex to be accurately simulated in real time. This is because tissue constantly deforms and reacts to pressure, requiring a large amount of computing power [30]. Furthermore, Coles explains that current simulations adopt a simplified generalisation of tissue movement as the computing power required to realistically simulate tissue is largely too expensive. However, studies indicate a positive consensus towards the implementation of haptic feedback systems and in the early stages of training. Highlighting that it may improve a trainee's performance in task specific training exercises [88].

The palpation physical examination is a practice that relies on a well trained sense of touch. The practice requires the touching of body parts or organs to determine certain characteristics such as size, shape and consistency. The examination has prompted a large amount of research and the creation of many haptic devices to create an accurate virtual scenario surrounding specific procedures. Devices such as the *Rutgers MasterII* force feedback glove, that featured multiple finger support and could simulate surface deformation [89]. Dinsmore et al used the device along with early virtual reality technology to create a simulation for finding liver tumours [90], similarly Langrana also used the device in the creation of a knee palpation simulator [91].

Coles et al compares three tactile actuators, piezoelectric pads, micro speakers and a pin array display developed by Salford University for a femoral pulse simulator

[92]. The pin array display contains 16 individually actuated pins which can be strapped to a users finger and cause a skin displacement of 2mm [93]. Coles reports that this pin array and piezoelectric pads are the most promising devices that are capable of replicating the subtle pulse. Ullrich discusses the improvement of the palpation examination training using virtual reality simulation and the *Phantom Omni* haptic device by *SensAble Technologies*. With the aim of creating a universal simulation rather than many that focus on specific procedures. Ullrich emphasises that participants felt uncomfortable with the hardware interface and initial feedback that it provided; however, this subsided the longer the session lasted [94].

A paper by Bouchard explored the treatment of arachnophobia with the use of virtual reality technology. During the study special measures were taken to ensure participants were at a similar anxiety level before starting the test and were required to stay after the test to wait for anxiety levels to fall once again before being allowed to leave. The study reports successful treatment of arachnophobia in that the majority of participants were able to approach spiders after the experience [95]. Results showed participants had changed their capacity to immerse themselves in an activity and reported that the participants presence scores increased as sessions continued, suggesting the introduction of an element of fear or anxiety would increase the level of presence a participant felt.

## 2.5.2 Haptics for Training Applications

Another large area of haptic research is training simulations, particularly within the medical field as explored in the previous section of this thesis; however, this is slowly expanding to other training applications. The use of simulators together with haptic devices is supported by multiple studies showing a positive effect in skills training [96]–[98].

Miles et al, developed a virtual simulation for rugby training, this experience is called *VERST* (Virtual Environment for Rugby Skills Training). It involved the use of a real rugby ball that was tethered to the players hand and within the

virtual environment, ball passing technique was focused upon, also weather forces upon the ball can be simulated. The use of a real rugby ball allowed the player to physically feel their hand positioning and the texture of the ball when executing a pass, making the action naturally intuitive and easy to replicate within a real rugby game [99].

Mäki-Patola investigated the creation and use of instruments within virtual reality. The instruments included a drum and a guitar. It was highlighted that the drum experience was underwhelming as the tactile feedback of physically striking an object, required to play a drum was absent. Meaning the use of such a virtual instrument would be limited as it would not be effective to utilise as a training aid. Regarding the virtual guitar a similar issue was identified, while the implementation allowed an unskilled user to play convincing music. Once again the lack of tactile feedback made locating the correct notes extremely difficult, preventing the virtual instruments use as a training aid [100].

Amirtha et al, created a simulation and haptic device with the aim of improving the training of vocational skills, in this case, surface mount hand soldering with tweezers. In order to gather frictional information on how people were holding the tweezers and success/failure results, a pilot study was carried out in which participants were required to solder both with and without tweezers. After analysing these metrics, a mechanical tweezer haptic device was developed, the device had adjustable weighted joints which created a friction force in the tweezers [101].

Seim et al investigated a method of passively teaching motor skills, in this case targeting the playing of songs on a piano, where no attention was actively given to learning. They aimed to investigate if tactile stimulation is enough to passively practice motor skills without audio. For the study a pair of gloves that were fitted with a micro controller, which controlled vibration motors on the back of each finger. These vibration motors were programmed to trigger in the same sequence and speed of a simple piano song. Participants were required to wear these gloves for a set period of time then play the song on a real piano, the amount of errors were compared to a control group that did not use the gloves. They concluded

that the gloves would be useful for very early learning stages and skill retention in times when a piano is not available. When using the gloves to train one hand neither audio or vibration alone resulted in reducing the error score more than training in the traditional method. However, when training both hands the error score was reduced, it is mentioned that this could be due to the initial struggle of using the device being reduced when the experience is synchronised across multiple limbs. In the case where participants wore the gloves and listened to the audio of the song higher levels of frustration were reported, emphasising that the gloves could also be seen as a distraction [102].

### 2.5.3 Haptics and Telepresence

Telepresence is another field of technology which benefits from interesting uses of haptics particularly in medical telerobotic applications. Brown et al, developed a wrist squeezing feedback system to be used with minimally invasive surgery that can indicate the strength they pull a suture or tactilely localise occlusions within tissue. The device was created to tackle the lack of rich haptic support in all FDA approved commercially available surgical robotic platforms. The device was constructed from a 3D printed mount which housed a servo motor attached to a hook and loop strap. The strap tightens around the users wrist in relation to the force being applied by the robot. To validate the device a study was carried out requiring participants to use the robot to navigate around a ring roller-coaster task. The participants were split into two groups some using the haptic device and some did not, this was so participants did not get used to the experience or alter the force applied which would corrupt results. The study concluded with the device successfully assisting participants in controlling the amount of force they used [103]. This work is supported by multiple studies investigating tactile feedback in tele-surgical and tele robotic platforms, assisting in the control of grip force, contact forces and accelerations [104]–[106].

Park and Howard presented a multi modal telepresence device aimed towards the visually impaired. Their solution utilised a *Kinect* RGB-D based depth camera which was attached to a mobile robot and a *Phantom Omni* haptic device. The

*Kinect* depth camera was used to build a virtual map which the user could explore through touch using the *Phantom Omni*. In order to validate the system they conducted a study using twelve participants, one of which was partially sighted and two that were registered blind. They were required to use the system in order to navigate the robot around a simple maze. The study concluded with the visually impaired participants having a lower success rate signifying that the system was not providing enough support for these participants [107].

Panzirsch et al, use the Oculus Rift virtual reality headset along with two *Phantom Omni* devices and a highly complex robot know as *DLR Space Justin*. The robot has fully controllable hands and cameras in its eyes allowing the user a first person view. The aim of the study was to perform basic nursing tasks with a humanoid robot through telepresence and evaluating force feedback. In the study participants were required to perform several simple tasks such as pointing at very specific positions and using tools using two different architecture channels. One of these channels with computed force feedback and the other with computed force feedback and measured force feedback. They found advantages of using a control approach for telepresence nurse tasks however, the different architectures were better for certain tasks. In the discussion section of the paper they emphasised that the immersion/presence factor may play a part in improving the study [108].

#### **2.5.4 Haptics in Games**

Kim et al research supports the use of vibrotactile feedback by looking at vibrotactile rendering which is the manipulation of vibrational waves to replicate a desired touch sensation. In the study an algorithm was developed that alters the vibrational wave forms between two vibration modules within a mobile device to replicate the touch sensation of a ball rolling around within a puzzle game [109]. In relation to this the company Senseg developed a haptic method, utilised in many modern mobile devices. This method uses a low electrical current in order to produce an attractive force, this laid above the devices screen in order to create desired textures and touch sensations [110].

Cenydd and Headleand carried out a case study on the popular virtual reality game, Ocean Rift. The case study highlighted and evaluated a number of interesting aspects that relates to this thesis regarding the design and player preferences when interacting within a virtual reality environment. The first being the addressing of positional tracking prompting the concern of using a reliable hand tracking method, which can potentially ruin the players immersion and pull them out of the experience. A further key point raised by this case study concerned the use of certain control methods as the majority of recent virtual reality controls involve holding the controller, which can feel like holding a tool or a weapon. Whilst an attempt at creating hand presence with these controllers is made, the functionality and amount of hand freedom they give are extremely similar. A final interesting aspect emphasised in the case study, was regarding the proposed movement method for motion control in the high end virtual reality headset implementation. It was initially proposed that in order to move around the environment the player mimics the motion of real-world swimming. It is mentioned that most of their users preferred a more direct method of moving where they simply move in the direction that they are pointing, ultimately, the feedback prompted the developers to use the pointing method as a way to control the direction of propellers [111].

Numerous studies have demonstrated that the introduction of haptic feedback can reduce error rates [112], increase efficiency [113] and increase user satisfaction [114]. Vibrotactile feedback is used when it is assumed that the device is in contact with the user so direct stimulation is applied, as in current virtual reality controllers. However, with the introduction of new control methods and with more studies choosing to use devices such as the *Kinect* or *Leap Motion* to track hand movements, allowing the player full hand freedom, with virtual reality headsets having devices in constant contact with the player may be phased out [68].

Pacchierotti et al, introduced a wearable cutaneous device that is to be worn on the finger called the *H-Ring*. The ring is constructed of two servo motors and a belt which tightens around the users skin designed to be used with hand tracking systems such as the *Leap Motion* and *Kinect* sensor. In order to evaluate this device a study using seven participants was carried out. Participants were required to move a block from one position to another with the *Leap Motion*



tracking their hand movements. It was found to effectively assist participants in providing grip feedback, although this device was not aimed to assist in immersion but rather to convey information on grip [115].

Gatti et al, investigated the use of haptics to improve the experience whilst playing a non technical game, in this case table football. They used this haptic feedback as a game design mechanic called interference play when the interaction between players is shaped in the form of collaboration/opposition. They implemented rules to allow users the ability to change the haptic feedback by interacting with the table football game. The friction of the opponents rods were changed when certain targets, placed on either side of both players goal, were hit. The idea was to alter the standard haptic experience in the game to provide a new game experience. They used a modified table football table on which they mounted the target zones and attached linear actuators to every rod which made the rods more difficult to move. It was reported users felt more connected with their team mate and opponents without hindering or giving any negative effects on the gameplay [116].

Yongseok et al, aimed to reduce the visual proprioceptive conflict (error tolerance of virtual reality finger tracking) with cutaneous haptic feedback. In this study a motion capture system was used to monitor the users positions and an *Oculus Rift* headset. The cutaneous device they used took the form of a fingertip device which used two servo motors to tighten a strap around the participants finger. Participants were required to carry out several simple object movement and interaction tasks. They concluded that the use of haptic feedback could extend the detection threshold of tracking errors, they recommended that a widely recognised design standard of an allowable error range before the experience made users too detached from the experience [117].

### **2.5.5 Haptics in Virtual Reality**

Hwang et al, presented an air haptics piano system aimed to provide a tactile experience in a HMD (head mounted display) virtual reality experience together

with mid air haptic feedback. The air piano device delivers tactile sensations of the naturally resisting forces of piano keys. In the study an *Oculus Rift* and a ultrasonic device mid air haptics display was used. The haptic display was capable of hand tracking with an integrated *Leap Motion* device and uses ultrasonic radiation delivered by a 14x14 array of ultrasonic transducers. In the study a combination of audio and visual feedback to enforce the perceived tactile feedback when touching a piano key up to the release of that key. Additionally, the vibration upon the release of the key and the returning force when releasing a key is also simulated. A total of sixteen participants took part in the study none of which were professional pianists. Three conditions were used: no feedback, constant feedback and adaptive feedback requiring each participant to play simple songs and chords. They concluded that the system was a successful multi modal virtual reality experience. In the discussion section of the paper it was reported that some participants felt uncomfortable with mid air vibrations, rather than real piano keys and emphasised that this could be due to the novelty of the experience [118]. This research is supported by multiple studies that highlight the use of haptic feedback in virtual reality can improve player experience and ability [119], [120].

## 2.6 Grand Challenges

Through reviewing the available literature a number of challenges have been identified, which are summarised in the following points:

- Contact haptic feedback appears to be the option to use; however, presence literature suggests that the use of extra wearable technology would dampen the experience and be viewed as intrusive.
- Current non-contact haptic research points towards two viable methods: ultrasound or air, both of which have a large obstacle to overcome in order to deliver satisfying feedback. Current literature points towards air feedback; however, the dispersion rate of air is very fast and transfer rate through air is very slow.

- The majority of research surrounding object characteristics is dated, with no research covering object characteristics that are more impactful or recognisable when experienced in virtual reality environments with modern virtual reality technologies or the impact that interacting with these has on presence. Additionally, haptic devices in research commonly have freedom limiting factors such as wires or a limited area of effect.
- Haptic devices found in literature currently do not satisfy the entire hand but only a section of it such as the finger tip. Current non-contact haptic devices that are beyond vibrotactile feedback are designed for a specific use/stimuli, this is not viable for video game or consumer level use as both of these factors require the device to be as universal as possible.

## 2.7 Summary and Discussion

This chapter has carried out a detailed review of the available research related to the topic of haptic feedback in video games. This satisfies one of the objectives of this thesis, specifically the objective of conducting an extensive literature review regarding tactile feedback in video games and related topics.

To begin the review of related research, presence in video games was investigated. From this analysis it was found that presence can be increased by introducing a story into the game which will engage players. This may be something to be avoided or utilised in the designing of the second study in this thesis as presence created from a story may artificially inflate results when the main concern of this thesis is the effect of haptics on presence. Furthermore, it was highlighted in papers regarding virtual reality and presence that wearable technology outside the technology required for the virtual reality HMD itself should be avoided. Finally, it was emphasised that the most contributing factor to presence is a player's motivation to play. This will be employed in the designing of the second study in this thesis.

While this research is primarily focused on the effect haptic feedback has on presence it is necessary to briefly investigate the literature surrounding immersion.

The second section of this chapter looked into the topic of video game immersion. The imaginative immersion aspect identified by Ermi and Mäyr [25] could be a mix of or confused with sensory immersion which has a similar definition to that of presence, highlighting the need for a cleaner definition of presence. In addition to this, any immersion in the game created as a part of this research is an advantage but as this research is only concerned with the effect on presence it is important not to get the two confused and misidentify what results may be showing. However as it is mentioned that imaginative immersion is commonly found as most prominent in role playing games it is more likely the immersion in game created as part of this research will be generated by sensory and challenge based immersion.

The third section of this chapter reviewed research concerning the sense of touch and the psychological and physiological aspects of touch was carried out. Through this review it was found that when trying to simulate touch sensations it is more effective to use sensations that users can pre-assume the feeling of. This is so a users mind may more fully complete a sensation if the method cannot completely replicate an exact sensation. Following on from this it was mentioned in multiple papers the value of using bimodal senses. The introduction of visuals can make touch sensations more engaging. A user can pre-assume what a texture or force may feel like sometimes creating a phantom force. Also discovered in this section was a well validated list of object textures and properties, used in a large amount of haptic related studies. Whilst this list could have been accepted and used in this research it would be dangerous to this research to assume this list holds true for virtual reality related haptics. A key reason for this decision is the level of virtual reality technologies has increased significantly since this list was created which could potentially change these object characteristics. Furthermore, none of the studies utilised this list to measure the impact on presence that haptics have on virtual reality experiences. However, these studies commonly mention bumpiness as the most recognisable texture both with and without visual perception on the material. These studies also highlight smooth textures as the least recognisable, consequently materials with these properties will be used in the initial study of this thesis. The final topic to be looked into in this section was haptic illusions, from this it was strongly suggested that feedback needn't

be as forceful as it would be in a none virtual environment. The way object speed, size and exaggeration of the users motions could be influenced to create pseudo-haptics, allowing the haptic device to be more universal. Of course with virtual reality tracking, emphasising the movements of the player would not be possible, as to not destroy the experience and presence factor since that is what we are measuring.

In the fourth section of this review the topics of contact and non-contact haptics were analysed. Through looking at the research related to contact haptics a common observation is that unless the haptics are delivered by a small form factor device that does not hinder the users freedom it is preferable to deliver stimuli to a user by a medium which allows them to have free hands. This observation was supported by the non-contact haptics research. By analysing research surrounding non-contact haptics it was found that of the two most viable non-contact methods (air and ultrasonic radiation) air appeared to be the most preferable. This is primarily due to the safety concerns of ultrasonic radiation and also the small area of effect it has. With this theisis focusing on virtual reality haptics it would be unacceptable to use methods that would hold the virtual reality technology back. However, research surrounding air haptics presented common issues such as the fast dispersion rate and low transfer speed of air. In addition to these issues the research found using air haptics were also limited by a small area of effect or requiring an object to be held in order to feel the force via the object.

The final section of this review investigates research that designed and developed haptic devices or that used commercially available devices. Through the review of this section a common issue of sensory overload either experienced during studies or emphasised as something to be aware of was repeatedly mentioned. Another issue repeatedly mentioned in research was the intrusiveness and freedom limiting factors of the devices, particularly in studies using a virtual reality headset. As many of these devices were required to be worn with cables connected to micro controllers which restricted movement. Additionally, it was also emphasised in these studies that participants should be allowed to get comfortable with the device and simulated sensations as results may be negatively effected by participants being put off by new experiences. Looking at the haptic feedback devices used in

research, it is clear that whilst having the same fidelity of haptics as the medical sector would be incredible, it is simply not required in the entertainment industry. The justification for this is that most of these devices were created for a very specific use case, creating a device that would be universal in the sensations it delivers but still keeping the fidelity of a device made specifically for that sensation is potentially impossible. Additionally, it could be argued that high fidelity haptics would be wasted on the average consumer as they will not have the sense of touch to the same level as a skilled surgeon. Finally, sensations usually experienced in many video games are simple, such as force and object handling, not micro texture difference detection or extremely subtle changes of pressure.

In the chapters to follow, limitations and challenges identified in this review of related works are tackled. Additionally, the useful findings also discussed in this summary will be used and a novel approach to non-intrusive virtual reality haptics is proposed. The results from this haptic device are then validated, analysed and discussed.

# Chapter 3

## The Impact of Haptic Modalities on Presence

To explore the impact of haptic modalities on presence, we must first establish whether different tactile sensations impact presence in a meaningful way. An initial study will be carried out in order to achieve this using a virtual reality environment. Furthermore, this study will provide an insight if any of the haptic modalities are viewed as more noticeable or valued by users when in a virtual reality environment.

This chapter will detail the testing methodology, design considerations and the implementation of the study. Finally the results from this study will be outlined and discussed, detailing how the findings guide the approach and development of the haptic device introduced in chapter 4.

### 3.1 Methodology

A framework was devised to investigate whether there is a disconnect between reality and the virtual world based on what is experienced by the player, or if the player's mind can bridge the gap between what is perceived and what is physically experienced. The study process consists of two stages, the first being a preliminary test designed to ensure that the participants can identify the properties of the objects to be used during stage two. This stage involved a box and multiple balls of different sizes, shapes and coated in different textures. The rationale for using

a mystery box was to ensure that the objects' properties can only be identified by touch and is not compromised by visual perceptions. Consequently, this will also give a small insight to the importance and effect that the visual perception of objects has on tactile sensations. Participants were asked to place their hand in the box and feel the object, they were then asked to write a description of the object on the answer sheet. This process was repeated five times with differently sized, textured and weighted objects. The order that these objects were presented was rotated for each participant in order to prevent order bias.

The second stage of the study required the *Oculus Rift* virtual reality headset along with the *Leap Motion* controller mounted on the front of the headset. The *Leap Motion* allows non-intrusive free movement of the participants' hands through its wireless tracking. Participants were presented with a simple environment of a desk and ball sitting on a stand. A physical configuration, similar to the virtual environment, was placed in front of the participant, with one of the objects used in the previous stage placed on the stand. A texture was applied to the virtual ball that may or may not correspond to the physical object, the physical object may also be a different shape, size or be weighted.

Participants were asked to interact with the object for thirty seconds, once the time had expired the participant was asked to place the physical object down and the virtual object disappeared. A new virtual and physical object was then placed in front of the participant and the time reset, this process was repeated seven times. The participants were split into two groups, the first group experienced the same textures that were shown in the virtual world which would be used as the control group. The second group experienced a variety of different textures, weights and shapes to what they were visually shown. Table 3.1 shows the pairings for the objects used physically and in the virtual environment for the second group of participants, these pairings were rotated for each participant.

During the study participants were video recorded in order to capture initial reactions when interacting with the objects. These recordings will be used for observational data during the final results analysis. It is anticipated that upon completion of the study, participants experiences may have been forgotten or



become dulled after multiple stages, potentially changing results, making it necessary to capture these reactions in real time. Upon completion of the study participants were asked to fill out the Witmer and Singer presence questionnaire. This will provide useful quantitative data regarding the impact that this type of feedback has on user presence when in an enhanced visual environment that is provided by the *Oculus Rift*. Additionally, the questionnaire allows participants to reflect and comment on specific experiences that they feel were noteworthy.

Texture Displayed in Virtual Environment	Physical Texture Used	Description
Sand	Sand	Ball is the same texture as displayed in the virtual environment.
Rock	Fur	Ball is a different texture than displayed in the virtual environment.
Sand	Sand (cube)	A cube is of the same texture is used, a ball is still displayed in the virtual environment.
Rubber	Rock (Heavier)	Ball is a different texture from the one displayed in the virtual environment and is weighted.
Aluminium	Aluminium (Heavier)	Ball is the same texture as the one displayed in the virtual environment and a heavier weight.
Fur	Rock (cube)	A cube is used instead of a ball and is a different texture than the one displayed in the virtual environment.
Rock	None	No physical texture is used.

**Table 3.1:** Study object pairings

Participants were required to read an information sheet outlining the reasoning and nature of the study. Before the study could commence a consent form was required to be completed and signed confirming that the participant understood and agreed to take part in the study. The consent form was kept separate from the questionnaire in order to keep the participants data anonymous. It was predicted that results gathered from a single crowd that may already be heavily experienced in virtual reality for example, would cause the effect to be dulled and visa versa. Consequently, no particular age, gender, gaming or virtual reality experience was targeted during participant recruitment. Participants were asked to gauge their gaming and virtual reality experience, which will be considered during the final results analysis.

### 3.1.1 Results Gathering Methodology

Both quantitative and qualitative data was gathered during each test session. An answer sheet was also used which was filled out by participants during the first stage of the test. Video recordings of each test session will be used for observational results, the audio from these recordings will be transcribed and be used if any common patterns or interesting comments are made. The questionnaire used for quantitative data is the Witmer and Singer presence questionnaire [17]. The questions used ordinal data in the form of a one to seven Likert Scale [121], with a result of one representing a negative position indicating the participant felt the experience was severely lacking. A score of four representing a neutral position and a seven indicating a very positive position.

For the purpose of this research we are using the definition of presence provided by Witmer and Singer, “the subjective experience of being in one place or environment, even when one is physically situated in another” [17]. The Witmer and Singer presence questionnaire targets specific areas regarding haptics and touch sensations making it ideal for this research. Additionally, the questionnaire mainly evaluates the contributing factors of presence rather than the presence of the experience itself, as suggested by Slater [122] and supported by Friedmann [123]. However, when this is teamed with the other qualitative data gathering methods previously discussed in this section, a large amount of data that comfortably covers all aspects will be collected. Furthermore, it was found during the review of the related works that the questionnaire has been used in multiple studies which also utilise virtual reality, further validating its use for this research. The SUS [124] and IPQ presence questionnaires were also taken into consideration for use in this research. The SUS questionnaire was deemed to be too general and broad for use in this study. Similarly the IPQ questionnaire was not specific enough in targeting the individual areas that contribute to presence, specifically haptic feedback, which is the core interest of this research.

The first stage of the initial study, required participants to feel an unseen object and fill out an answer sheet simply detailing properties such as the texture, weight

and shape of the object they are touching. The answer sheet is comprised of five spaces corresponding to five rounds, in each space they will write descriptions of what they are experiencing when feeling the object. The rationale of this initial stage is to ensure that the textures used can be identified without any visual suggestion that seeing the object may provide. This will strengthen the overall results from the test as participants will have confirmed or not confirmed that the textures used are identifiable.

The final data gathering method being used is video recordings of each participant during the study, providing consent is given. These video recordings provided valuable observational data, allowing the initial reaction of participants interacting with the objects to be captured and analysed. The recordings may also capture noteworthy comments and thoughts expressed by participants that are unprompted, as they would be in an interview setting. In the event that a participant does not agree to be recorded, simple observational notes will be taken during the test. These notes will not be as highly regarded as the recordings and will be marked as “not-recorded” during the results analysis.

### **3.1.2 Beta Testing**

To ensure the study environment will perform as expected a beta test involving a small amount of participants will be carried out. The beta test will follow the testing and results gathering methodologies outlined in this section. This will provide an insight on how participants will interact with the environment and unforeseen concerns during the implementation of the study will be revealed and rectified avoiding any test experiences that may corrupt the results.

### **3.1.3 Data Analysis**

The Witmer and Singer presence questionnaire use Likert scale style questions which will be analysed by calculating averages and significance values through appropriate statistical tests. These results will also be graphed to provide an easy

understanding and aid the drawing of conclusions. The answer sheet responses will be used to accompany these results so in the event a participant did not correctly describe an object, stages that use that object can be approached in an alternative way or disregarded. Any common patterns that may emerge from these answer sheets will also be analysed as it is important to identify any potential reasons why these patterns are present and which objects they are relevant to. The video recordings will be transcribed and observations will be used in support of results and any conclusions drawn.

## **3.2 Design and Implementation**

In order to achieve the final study environment for the study, a number of different aspects needed to be considered before the study was ready for the beta testing period. The design considerations and implementation of these design choices will be discussed in this section.

### **3.2.1 Textures and Shapes and Verification**

In order to correctly gauge the impact that haptic feedback has on presence in virtual reality video games both physical and virtual types of textures need to be considered. As mentioned in the related work chapter of this thesis there are pre compiled lists of textures and object dimensions that have been identified as valuable in haptic research and verified by multiple studies [43]–[46]. Whilst these dimensions could have been accepted and used for this research, there is potential for these to no longer hold true when used with modern virtual reality technology. It would be dangerous to assume these dimensions are correct for this research as the majority of studies which utilised these dimensions restricted participants visuals and freedom of movement.

The difficulties regarding the textures came from the requirement that the textures needed to be easily identifiable from each other, a virtual texture that closely

corresponded to the physical objects texture needed to be found. Additionally, a variety of textures should be used as a large amount of virtual reality games are currently set in space or in a futuristic setting where the textures used are largely smooth and fairly simplistic. Finally, it needed to be considered how these textures would be presented to participants in a non-restrictive fully interactive manner both virtually and physically.

It was decided not to use textures popular in virtual reality games as these textures would be too difficult to distinguish and would not provide any real indication of the impact on presence. Consequently, a variety of textures were used, previously listed in table 3.1 in the methodology section in this chapter, some of which represented the extreme opposites of each other and some similar to each other. The textures similar to each other allowed the measurement of how obvious, if at all, a texture has to be in order to be identifiable and what impact subtle differences has on presence. This resulted in the textures chosen to be used which were, fur, sand, aluminium foil, rubber, plaster (to simulate rock).

An additional investigation in this study was also to identify the importance users placed on certain properties of objects such as weight and shape. Consequently, a the object that these textures would be applied to was considered. The shapes used would be required to be easily created and textured both physically and in the virtual world. However, a selection of shapes would also be required so as to gauge the users reaction of various shapes and observe the disconnect experienced when an unexpected object was used. With these constraints in mind it was decided to utilise spheres and cubes, each with the previously mention textures applied and a further set of these with altered weight.

The final issue to be tackled regarding the objects is the verification that the physical textures accurately replicate the correct texture once they have been applied to the objects. This was achieved by a simple mystery box style game, discussed previously in the methodology section of this thesis, in which the participant would place their hand in the box and describe the texture of the object inside. This method was decided upon as the lack of visual information about the object would mean the description of the texture would be purely from

the tactile feedback of the objects. Furthermore, the mystery box method gave a small insight into the impact that visual information had when identifying texture, particularly with textures that are similar.



**Figure 3.1:** Image displaying a selection of the different textures, shapes and sizes used.

### 3.2.2 Virtual Reality Headset

When considering which virtual reality headset to use, the two options being the *Oculus Rift* and the *HTC Vive*, a few key characteristics needed to be reviewed. The key aspect to be considered is the way the headset would be used, for this initial study participants are not required to move around a play area, instead they will act almost like a turret where the participant is in a fixed position and can inspect the environment from that location. In this case *Oculus Rift* would be the preferable headset to use as its simple set-up lends itself well to desk usage. Additionally, this study does not require the use of any current controllers available for the *Oculus Rift* or the *HTC Vive*, which will be discussed further in the control methods section of this report. As the *HTC Vive* comes boxed with the wand controllers and the base *Oculus Rift* is not shipped with the touch

controllers, the *Oculus Rift* is again a preferred choice in terms of cost as the controllers will not be needed.

### 3.2.3 Control Method

A significant challenge regarding the design and implementation of the study, involved the selection of a control method that would suit the study. In order for the control method to be appropriate for the study it must allow participants to interact with virtual objects with a completely free hand, as in some cases it would be required to interact with physical objects at the same time. Consequently, as previously mentioned, the standard *HTC Vive* wands and the *Oculus Touch* controllers would not suit this use as they are required to be held. This called for a control method that individually tracked finger movement and hand position, to achieve this two methods were considered.

One of the methods considered was the creation of a pair of glove controllers utilising an *Arduino*, accelerometer and gyroscope module along with flexible resistance sensors to attain individual finger tracking. The gloves would be wirelessly connected to an additional *Arduino*, through the use of the *XBEE* RF module, which would pass the movements to the Unity game engine via a serial connection. Providing the method was correctly implemented, it would be an accurate and reliable method of freely interacting with both virtual and physical objects. However, if it was not implemented correctly or hardware failure occurred, it could lead to a frustrating experience for participants and ultimately cause any results gathered to be void.

The alternative method considered was to use the *Leap Motion* controller along with the virtual reality headset mounting bracket and the *Leap Motion* SDK in order to tailor the behaviour to the requirements of the study. The *Leap Motion* tracks hand position and individual finger movement through the use of infra-red in a 180 by 180 degree FOV (field of view). Furthermore, the SDK already includes fully rigged and movable hand models and grasping functionality. Using the *Leap Motion* controller would result in a large amount of time saved, as

the technology has already been tested and well implemented. Additionally, the support of large experienced *Leap Motion* community was available in the event of troubleshooting or code adjustment issues. On the other hand, the critical downside to this controller is that it uses infra-red to achieve its tracking, which can be inaccurate and much like the previous method could result in a frustrating experience and corrupting results.

After considering and comparing the advantages of the two control methods, it was decided upon to use the *Leap Motion* controller for the study. The key factor that lead to this was the ease of implementation with the *Unity* game engine along with the already implemented grasping functionality and created hand models. Furthermore, this is a study primarily for data accumulation in order to verify and base the research on. The time commitment required to design, implement, test and verify the effectiveness of a glove controller with similar functionality to that of the *Leap Motion* would be too great.

### 3.2.4 Physical Set-up

The physical set-up of the study is fairly simple, it involves a small stand, which the objects will be placed upon, a table and the *Oculus Rift*. The core issue of this set-up was matching the placement and size of virtual environment objects to that of the physical objects, such as the table. This issue needed to be handled effectively as the inaccurate representation of the environment could negatively effect participant presence and performance in the study, which would corrupt results. Three methods were considered to tackle this issue which would allow the physical set-up to mimic the virtual set-up.

The first method required the primary researcher to physically touch the boundaries of the table and the position of the stand for the objects, prior to the participant starting the study. When the boundaries and object positions are touched the controller position will be logged and the objects will be spawned in and correctly scaled. The main issue of this method relates to the control method the study uses, as discussed in the control method section of this thesis. This is



because the *Leap Motion* controller is attached to the *Oculus Rift*, meaning there is no static reference point in order to base the logged positions from. Additionally, as the *Leap Motion* is attached to the *Oculus Rift* HMD, the participants height and sitting positions would alter these positions. A further issue with this method is that the *Leap Motion* has no button or confirming gesture that could be performed when the physical position has been touched, unlike a controller such as the *Oculus Touch* controllers as a button could be pressed when the correct location is identified.

An alternative method involved the use of an *Arduino* and a multiple accelerometer gyroscope module. As with the previous method this required the primary researcher to set the locations up prior to the study being initiated. The *Arduino* would orientate the modules setting the initial position to zero, these modules would then be placed at the left and right boundaries of the table and in the ball stand position. The key advantage of this being that this set-up would only be required to be performed once per day. The main disadvantage of this method is the time required to create and verify that the system works accurately and reliably.

The final method considered required the study set-up to be permanently assembled in an area and the participant to perform the orientation action every study session. This method relied on the accurate modelling of the objects and table as these sizes would not change, only the location of the models would be altered. Two points would be marked on the table where the participant would place their hands, the location of the participants hands would then be logged and the virtual objects would be spawned around the participant using the hand location as a reference point. This method had many advantages as it could be achieved using the *Leap Motion* and with no additional hardware. Additionally, it would allow the environment to match each participants natural sitting position and height, removing any potential factors that could artificially affect presence.

After considering these methods of accurately replicating the physical environment it was decided to use the third method, utilising the *Leap Motion*. The main factor that lead to this decision was that the method used the selected control

method and wouldn't involve any time consuming development. Whilst the method required each participant to perform the orientation task in order to spawn the virtual environment, this also meant that each study session would be tailored to the participant. In order to achieve this two raised points were attached to the physical table which the participant would be able to locate and place their thumbs on.



**Figure 3.2:** Image of the physical set-up of the study.

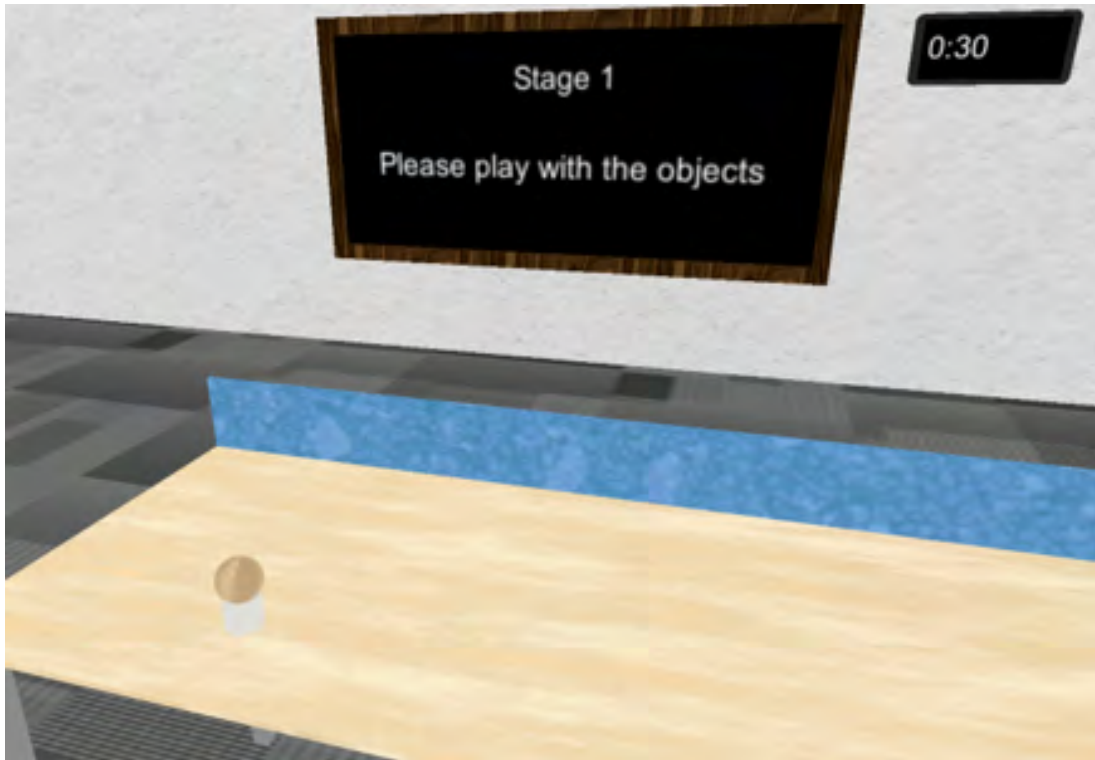
#### 3.2.4.1 Virtual Environment

Like the physical set-up the virtual environment is simple, involving a model of a room, with a clock, board and table. No design considerations were made during the development of this environment, instead the development was guided by the design considerations discussed in the previous sections. The main aspect that the environment had to accommodate was the positioning of the virtual objects. In order to achieve this the virtual environment was split into two separate modules. The first module consisted of the room, clock and board models which would instruct participants. This would be centrally placed based on the position of the participants' hands. The second module was simply made up of the table model with the ball stand, which would be positioned according

to the participants' hands, ensuring that the ball stand would be directly in front of the participant, matching the physical environment. As the correct positioning of the room and table were the most important part of the implementation of this study it was decided to control the instantiation of the models with a keyboard button. This would be pressed when the principle investigator was satisfied with the participants' hand placement, causing a fade to black and a fade into the environment to avoid any discomfort that would be felt from instantly changing location.

As participants had a strict time limit of thirty seconds for each object a clock was placed in front of the room which would countdown and reset every thirty seconds. Upon the expiration of each thirty seconds the current object would disappear and the next object would be placed on the stand. In addition to this, in order to keep the manual interference to a minimum, if the object was dropped and lost by the participant a new object would automatically be instantiated on the stand. The physical object would be taken from the participant and placed back in the physical stand.

Finally, as it was critically important to keep any interference from the principle investigator to a minimum a black board was placed in front of the room which would provide instructions to the participant. This would allow the participant to focus on the experience rather than having to hear an outside voice which would negatively affect presence scores.



**Figure 3.3:** Image showing the virtual environment for the study.

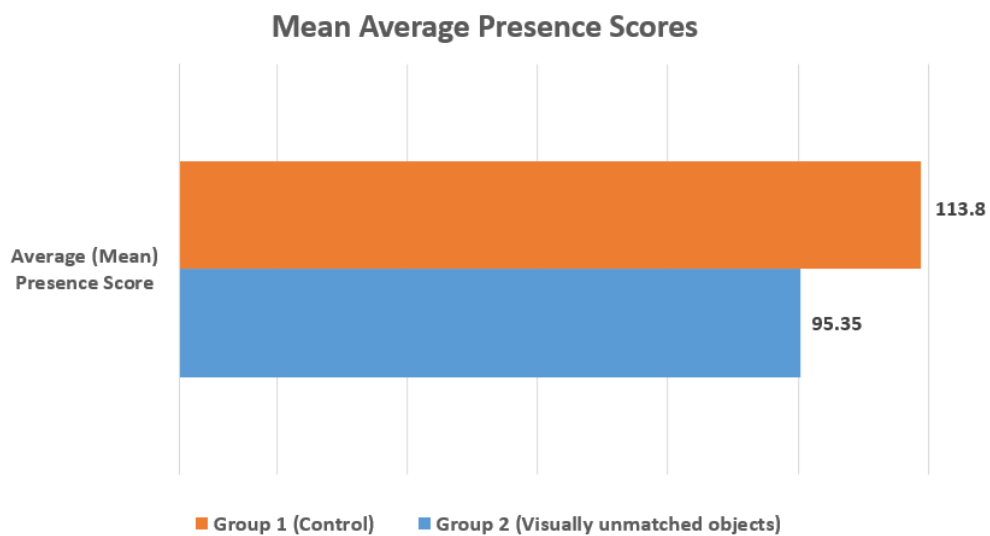
### 3.3 Results

A revised version of the the Witmer and Singer presence questionnaire was used with the addition of two optional questions as the study was concerned with haptic feedback making a total of 22 questions (see appendix A). The maximum score which indicated to the best experience of presence was 154. These questions each related to certain sub categories of: realism, possibility to act, quality of interface, possibility to examine, self-evaluation of performance and haptic sense. In order to gain a total presence score per participant from the questionnaires, scores from questions 14, 17 and 18 were reversed and added to the sum of the remaining questions. All of the final presence scores were then totalled together in order to achieve a single total presence value, this process was carried out for both groups, resulting in two summed up presence values for each group.

The study was run for a total of three weeks with 36 participants. Of these 36 participants 69.4% (25) were male and 30.6% (11) were female. The participants had a median average age of 22 (Mean of 22).

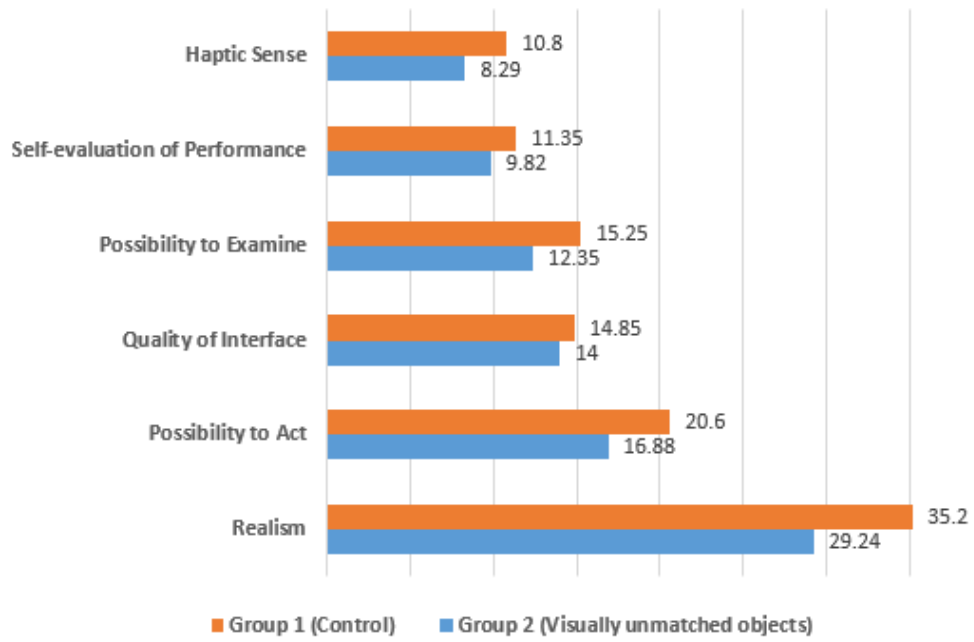
The overall presence scores of both the control group (group 1) and participants that experienced different textures (group 2) were compared using an independent t-test. On average, the control group (Mean = 113.8, SD = 12.85) reported higher presence scores than group 2 (Mean = 95.35, SD = 11.62), shown in figure 3.4, indicating that experiencing mismatched tactile and visual feedback has a negative effect on presence. This difference, 18.45, 95% confidence interval [10.2, 26.69] was statistically significant,  $t(35) = 4.54$ ,  $p < .001$ .

Figure 3.4 shows the total and mean average of the presence scores for the two groups. Looking at this graph there is clearly a large difference between the total presence scores of the control group and the group with visually unmatched objects. Figure 3.5 displays the mean average presence scores for the questionnaire's sub-categories. These results show a clear difference between the two groups with the visually unmatched group consistently scoring lower. The significance values for each of these sub-categories are shown in table 3.2.



**Figure 3.4:** Graph comparing the mean average presence scores for groups 1 and 2.

### Mean Average Presence Subcategory Scores

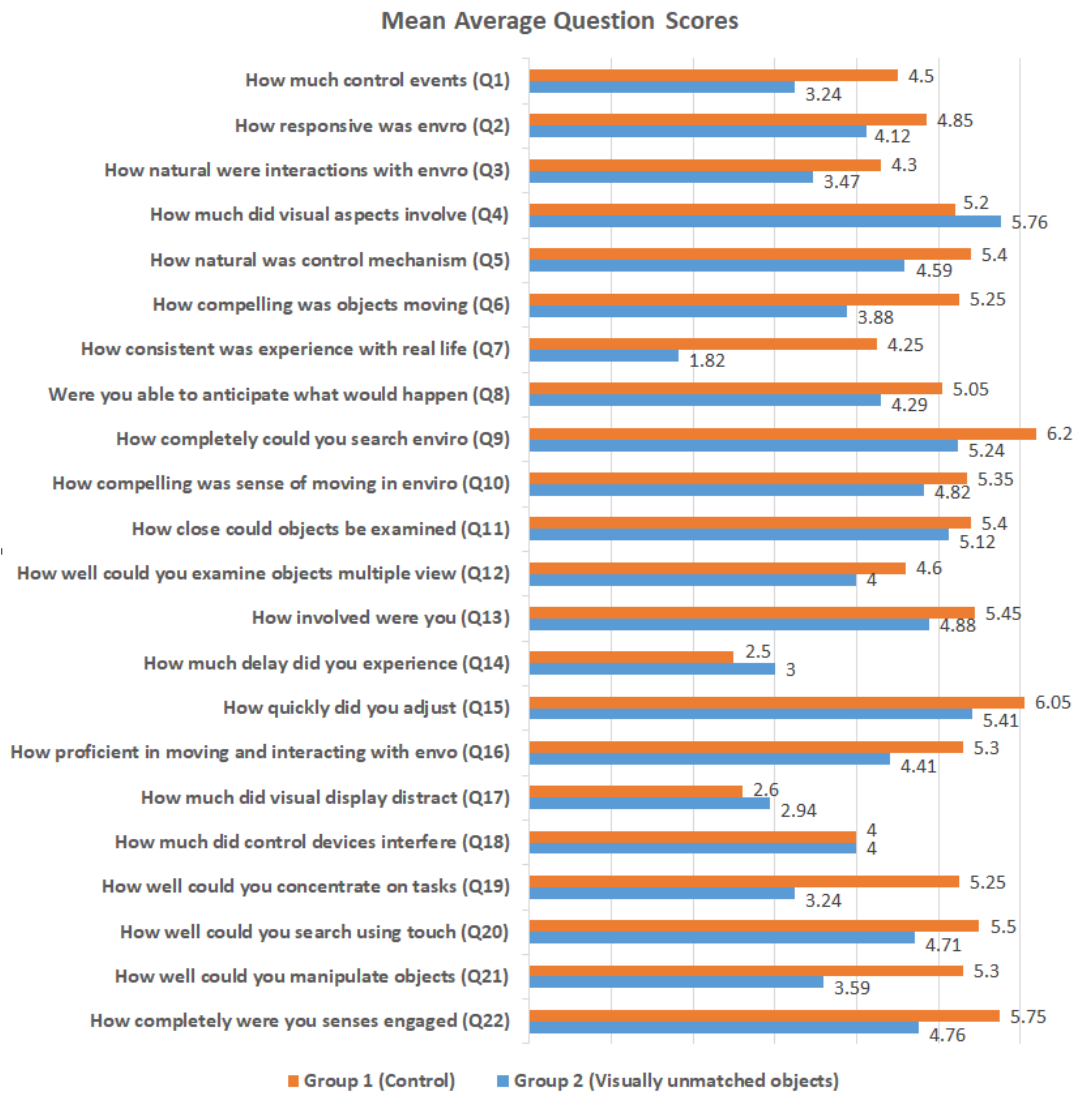


**Figure 3.5:** Graph comparing the mean average presence subcategory scores for groups 1 and 2.

Subcategory	Difference in	Significance
	Mean	(p value)
Haptic Sense	2.5	<.001
Self Evaluation of Performance	1.52	.044
Possibility to Examine	2.89	.004
Quality of Interface	0.85	.04
Possibility to Act	3.71	<.001
Realism	5.96	<.001

**Table 3.2:** Table showing the difference in mean and significance scores from an independent t-test for each subcategory.

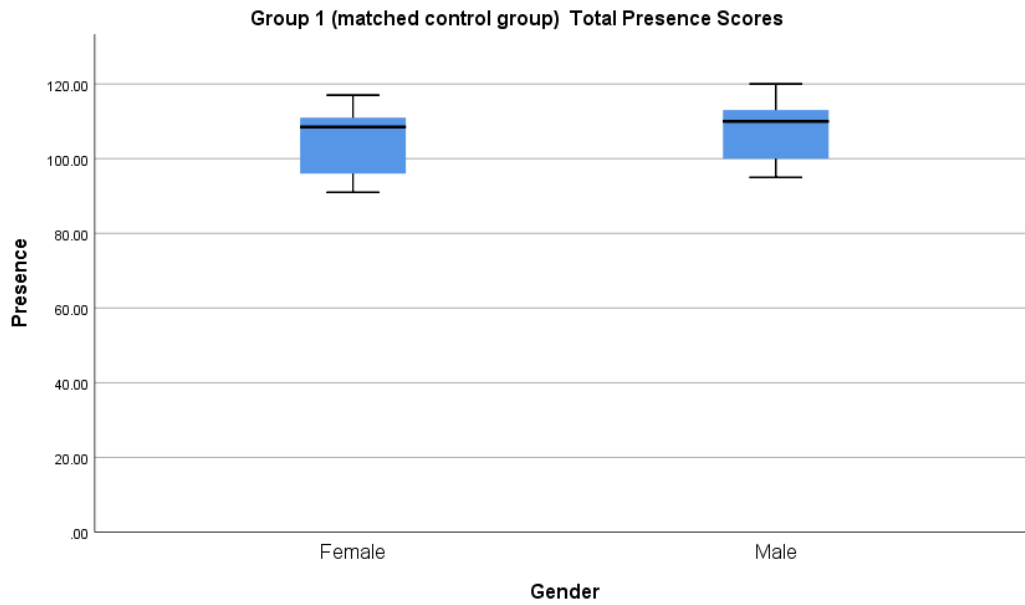
Figure 3.6 shows the mean average scores for each question for both groups, displaying a clear trend in lower scores for the second group, particularly in the haptic related questions. A number of these questions show large differences between the two groups. Some of the most noteworthy differences which will be covered further in the discussion section of this chapter are questions: 1, 7, 14, 19 and 22.



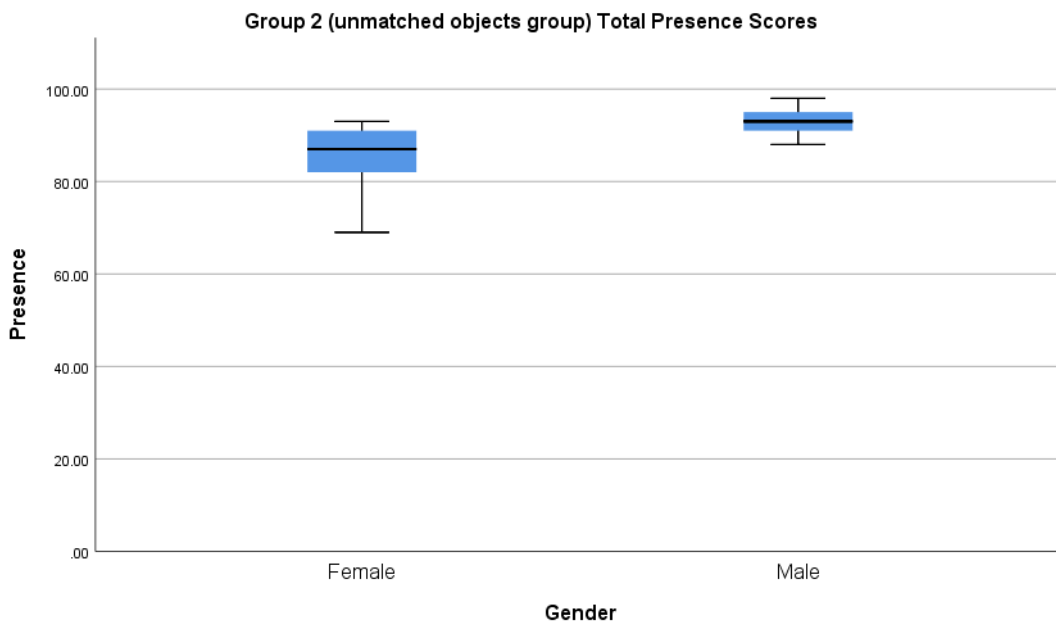
**Figure 3.6:** Graph comparing the mean average scores for each question in the presence questionnaire between groups 1 and 2 (without questions 14, 17 and 18 reversed).

Participants were also asked to score themselves on their virtual reality experience on a 1-7 point Likert scale. Both the female and male virtual reality experience alongside their presence score for both the control group and unmatched group can be seen in figures 3.7 - 3.10. As there was an uneven number of females and males per group these samples were taken to remove the uneven sample. The graphs show the impact that haptics may have had on presence was not gender dependent, with the average presence scores in the control group following the trend of being higher than the second group. Additionally, these illustrate that the participants virtual reality experience did not greatly impact the results as the large difference in virtual reality experience between male and female participants did not greatly alter the trend of scores given by those with high experience.

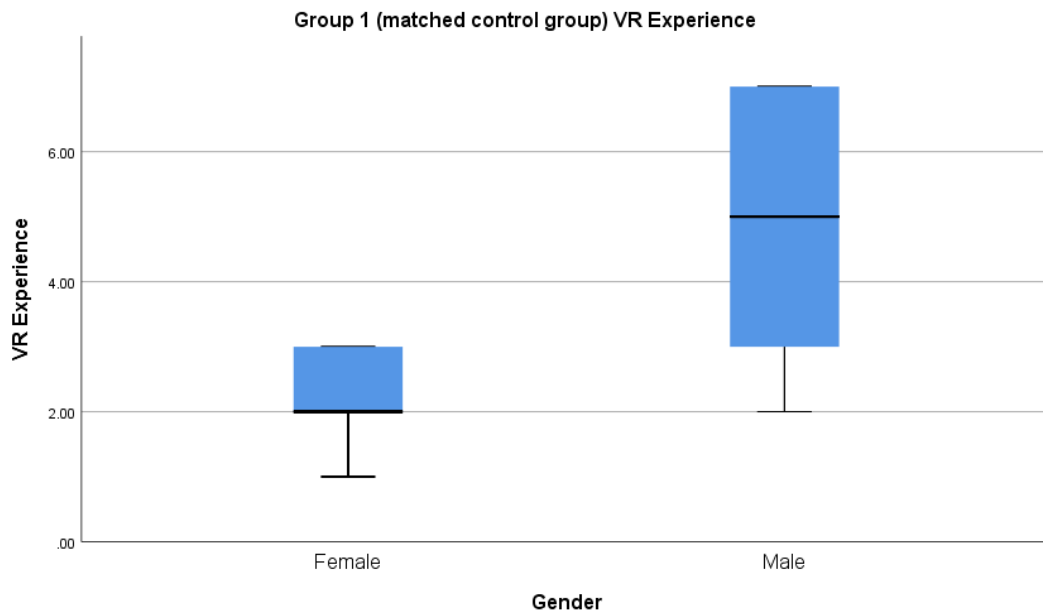




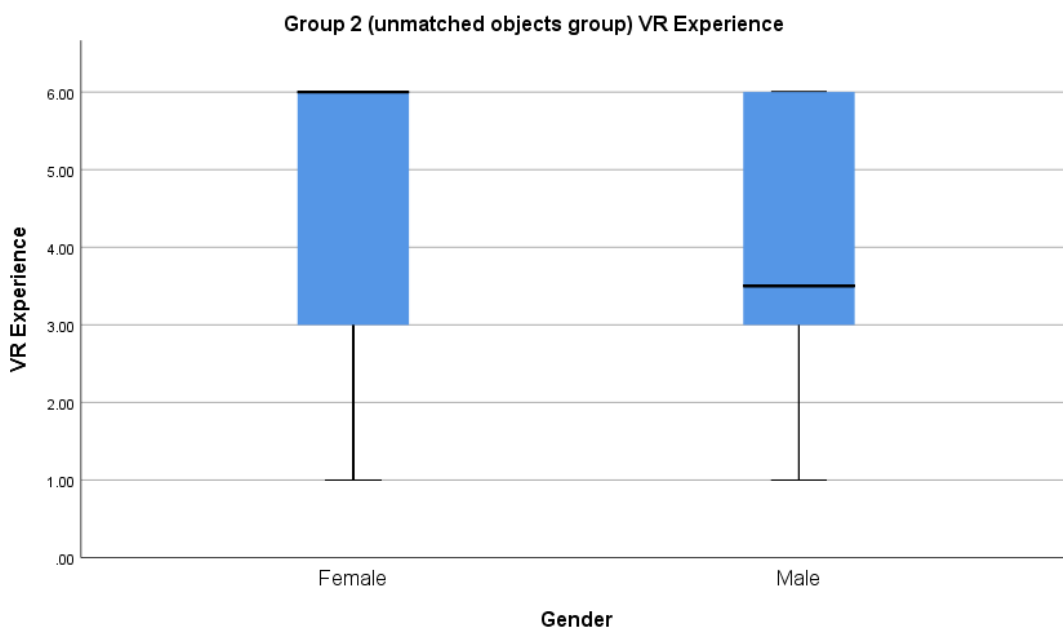
**Figure 3.7:** Graph comparing the difference between the male and female presence scores for group 1 (control matched object group).



**Figure 3.8:** Graph comparing the difference between the male and female presence scores for group 2 (unmatched object group).



**Figure 3.9:** Graph comparing the difference between the male and female virtual reality experience scores for group 1 (control matched object group).



**Figure 3.10:** Graph comparing the difference between the male and female virtual reality experience scores for group 2 (unmatched object group).

These results are also supported by participants reactions captured by video during the study. All participants in the second group were seen reacting cautiously or surprised, with verbal expressions that indicated caution after their interaction with the first stage. Participants were seen poking at the object first or looking at the object while it remained on the table. Similarly to this participants of

the control group reacted in a cautious way but did not show signs of surprise. Instead they more readily explored the objects, bringing the objects close to their face and rotating them to view different angles, to support this audible signs of interest can be heard. Participants that scored themselves high on their virtual reality experience more readily accepted the lack of physical objects, stopping their fingers themselves in order to grip the virtual object. In comparison to this participants which scored themselves low on their virtual reality experience, were more troubled by the lack of physical feedback with all participants gripping the object tightly causing the virtual hands to clip through and propel the virtual object. Finally, the large majority of participants from both groups commented on the shape of the object first, rather than weight, size or texture, even when the object was the same shape that was visually shown. Furthermore, only four participants, all in the second group, commented on the size of the object and none commented on the weight of the objects.

### 3.4 Discussion

The results from this study indicate that haptic feedback has an impact on presence in virtual reality environments. This can be clearly seen by the significant gap between the two total presence scores of participants and is supported by the haptic subcategory scores. This also indicates that for the sample of participants used in this study, the hypothesis mentioned in the first research question in the introduction chapter of this thesis, “A users mind will bridge the disconnect that is experienced when something is physically perceived but not visually experience”, is disproved. This goes against findings discussed in the related work section of this thesis. It can be hypothesised that the cause of this could be that the virtual environment was very much a study environment, making participants aware that they were in a study. An additional reason for this is indicated by the low scores given by both groups on the control interference question of the questionnaire (question 18). The *Leap Motion* controller was the only option to use for this study without creating a custom control solution as previously discussed; however, it was observed that the *Leap Motion* had difficulties tracking participants with

smaller hands. A further potential reason for this could be due to the novelty of the experience and the unease of participants which was observed through the reviewing of the video recordings and is supported by findings discussed in the related works. An attempt to reduce this was made by allowing participants as much time as they desired in the practice level in order to become accustomed to the controls and experience.

The large mean differences for some of the questions of the presence questionnaire (shown in figure 3.6) provide an interesting insight into what effects the mismatch of haptic and visual feedback has on presence. The first question of the presence questionnaire (How much were you able to control events?) shows a mean difference of 1.26. This indicates that participants felt less in control when tactile feedback is not accurate to what they are perceiving. Question 7 (How much did your experiences in the virtual environment seem consistent with your real world experiences?) had a mean difference of 2.43, suggesting that mismatching the tactile and visual senses had the desired effect on participants. The 14th question (How much delay did you experience between your actions and expected outcomes?) had a difference of only 0.5 with the second group scoring higher. This indicated participants took longer to register the objects properties when they were different to what they expected. Question 19 (How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?) shows a difference of 2.01, reveals that participants had difficulties concentrating, even on the simple task given in this study, when visual and tactile feedback are mismatched.

Results also suggested the impact that haptics have on presence is not affected by gender or the participants level of virtual reality experience. This is proven by a trend being observed and followed showing consistent higher scores for the control group and lower scores for the second group regardless of their gender or virtual reality experience. The conclusions discussed in this section are supported by observations made by reviewing the video recordings. A particularly interesting trend which was not formally measured for, found through reviewing the video recordings was the reactions to the shape of the objects over all other object characteristics. This indicates for the sample of participants used in this study

the shape of the object was viewed as more intriguing and comment worthy than the other object characteristics. Suggesting that for participants in this study a valuable haptic modality is shape, which further suggests the more obvious modalities are the more valued they are.

Results from this initial study show haptic feedback does have a significant impact on presence. The findings discussed in this section will be used as guidance to create a haptic device and game environment in order to verify the effectiveness of the device. The findings of this study suggest use of the *Leap Motion* would be disadvantageous as the system is too unreliable for accurate tracking and requires the *Oculus Rift* to be pointing in the same direction as the users hands. However, the non-intrusive factor of the *Leap Motion* was seen as a beneficial factor which was also supported by literature discussed in the related work chapter and will be considered in the design of the haptic device. The suggestion that shape is an important modality indicating that the more obvious modalities are more valuable, this will be aimed for in the design of a haptic device, moving to the simulation of more obvious forces rather than subtle textural differences. In addition to this with air being strongly suggested by literature this could be a preferable platform to base the device on.

# Chapter 4

## Air Cannon: A Non-Intrusive Haptic Device

As discussed in the previous chapter, results from the initial study indicated that forces and shapes were the key haptic modalities to impact presence when used with virtual reality. As this research aims to create a non-intrusive haptic device, the related literature strongly supports non-contact haptics. Consequently, the haptic device was created around the medium of air which is strongly supported by the literature. In this chapter the conceptualisation and implementation of this device will be detailed. In addition to this a study will be outlined in order to verify the devices effectiveness in terms of the impact on presence in comparison with current vibrotactile feedback.

### 4.1 Methodology

To evaluate the devices impact on presence and effectiveness as a non-intrusive haptic device that could be readily adopted in a generic home virtual reality set-up, a framework was devised. This framework would compare the new device with the standard vibrotactile haptic experience. The study involves the *Oculus Rift* along with the *Oculus Touch* controllers, a set of noise cancelling headphones and the new haptic device. The virtual environment of the study takes the form of a futuristic goal keeper game.

The study process required participants to play the goal keeping game three times for a duration of five minutes each. The participants played the game using vibrotactile, air and no haptic feedback at all. At the end of each of these playthroughs participants were asked to complete the Witmer and Singer presence questionnaire [17] and at the end of the study session participants were required to complete a custom questionnaire.

In order to set-up the game the participant was required to perform two tasks which set up the environment and haptic system. The first task was to perform a T-pose, which adjusted the width of the goal to that of the participants reach. This was to primarily address health and safety concerns as it ensured that participants would not be required to move and jump around a great deal and potentially tripping over the wire that comes from the *Oculus Rift*. The second task was to touch the nozzle of the air cannon and press the trigger on the ‘*Oculus Touch*’ controller. This was required to position an anchor in the virtual world which allowed the cannon to track virtual objects, this will be discussed further in the design and implementation sections of this chapter. Of course this only has an effect during the air haptics portion of the study; however, as participants are not informed which order they will be experiencing the different haptic mediums, in order to prevent order bias, it is required for all three conditions to avoid skewing results.

Once the two set-up tasks are completed a countdown from three begins and balls begin firing towards the participant. In order to prevent participants becoming bored, which naturally lowers presence results, the balls velocity and direction change each time a ball is fired. Participants accumulate a score which will be logged upon the completion of each condition. When a ball is saved the score is increased by 100, if it is missed it is decreased by 100. At the end of the five minutes the balls stop firing and a message is displayed asking the participant to remove the headset in order to complete the presence questionnaire for that portion of the study. In order to complete the experience an arcade like soundtrack was added. This soundtrack also aided in the masking of the noise created by the air compressor charging and the cannon firing which, as found in the related literature, may cause phantom or false sensations. To further mask

these unavoidable sounds from the cannon participants were required to wear a set of noise cancelling headphones.

No specific instructions were given to participants for clothing that should be worn prior to participating in the study. This was to aid the confirmation that the device could be comfortable and easily used in an at home gaming environment. As to be expected clothing ranged from cotton vests and t-shirts to full sleeved shirts and jumpers. As with the initial study previously introduced in this thesis, participants were also video recorded throughout the study sessions, this was to capture any noteworthy comments and participants initial reactions which will be used for observational analysis.

Participants were required to read an information sheet outlining the reasoning and nature of the study. Before the study can commence a consent form was required to be completed and signed confirming the participant understood and agreed to take part in the study. The consent form will be kept separate from the questionnaire in order to keep the participants data anonymous. As in the initial study no particular age, gender, gaming experience or virtual reality experience was targeted during recruitment. Participants were asked to gauge their gaming and virtual reality experience on a 1-7 Likert scale.

#### **4.1.1 Results Gathering Methodology**

Both quantitative and qualitative data was collected during the study. A custom comparison questionnaire (see appendix B) was used which was given to participants at the end of the entire study. This questionnaire is comprised of nine questions with the option of four responses for each and used to support recording observations and results gathered from the presence questionnaire. In addition to this the Witmer and Singer presence questionnaire was used.

Finally, video recordings were taken after participants gave their consent. These recordings potentially provided valuable observational data, allowing the analysis of the participants body language. Additionally, these recordings may also



catch unguided noteworthy comments or thoughts expressed by the participants. As with the initial study if a participant did not agree to be recorded, simple observational notes were taken during the test, which are not as highly regarded as the recordings and are marked as "not-recorded" during results analysis.

### **4.1.2 Beta Testing**

To ensure the haptic device performs as expected a small test was carried out after the device construction was completed, involving a small number of participants. The test involved a very simplistic set-up of an *X-box Kinect* and the device. The device was set to track the right hand of the participant using the *Kinect* and periodically fire a blast of air. The participants were asked to indicate when and where they felt the blast of air which allowed any potential issues to be identified and addressed at an early stage.

A second beta test was carried out upon the completion of the virtual environment which involved a full run through of the study with a small amount of participants. The beta test followed the testing and results gathering methodologies outlined in this section. This highlighted any issues that needed to be addressed regarding the virtual environment or methodologies prior to carrying out the study.

### **4.1.3 Data Analysis**

As previously mentioned in the initial studies data analysis section the Witmer and Singer presence questionnaire was analysed by calculating averages and significance values through appropriate statistical tests. Findings from the video recordings and results from the custom comparison questionnaire was used to support results from the statistical tests. Additionally, the custom comparison questionnaire was analysed to identify any common patterns that may have emerged.

## 4.2 Design

In order to achieve the final haptic device and study environment a number of design considerations needed to be made. As air has been selected as a haptic medium a number of key challenges would need to be addressed: the fast dispersion rate of air; keeping the sensations consistent; and creating a device that is capable of virtual object tracking. These considerations regarding the design of the air haptic device and study environment will be discussed in this section.

### 4.2.1 Air Source

As previously mentioned it was decided to use air as the haptic medium for this device, which is supported by the reviewed literature. The literature also strongly supports the use of non-contact haptic devices, further pointing towards air as an appropriate haptic medium. In addition to this, findings from the initial study suggest that certain haptic modalities, which could be created easily using air, would be effective in achieving a satisfying haptic experience in virtual reality.

With air decided upon as the haptic medium, the type of the air required needed to be considered. Due to the ease of acquiring an appropriate air type for this device there were two choices which could be used, compressed air or spring/diaphragm delivered air.

A design involving diaphragm air would be similar to Disney's *AIREAL* device, discussed in chapter two of this thesis. This could be achieved using the cone of a dismantled subwoofer speaker as the diaphragm. An aperture could then be created which would shape the air to form a vortex, allowing the air to travel further. This method would address the air dispersion rate issue and also the safety concerns which come with compressed air. The triggering mechanism would also be straight forward as a voltage would simply need to be passed to the speaker to cause the speaker cone to vibrate. There are two main concerns with this approach, the first being the sound created by the speaker upon firing, which

if heard by participants could cause them to pre-empt the sensation, influencing results. The second concern is the amount of testing and verification that would be required in order to machine an effective vortex creating aperture.

An alternative approach to the diaphragm method would be a deconstructed spring powered *Airsoft* or *Nerf* gun. This approach would address the noise issue of the diaphragm method; however, the blast of air would not be as consistent. In addition to this the deconstructed gun would have to be fairly powerful in order to deliver a satisfying blast of air at the distances that would be required for the device to not limit player freedom. A final concern with this approach was that the trigger mechanism would need to be fairly complex and involve careful calculation so that the trigger is pressed milliseconds before a blast of air is required.

A design using compressed air comes with two choices for the air source, the first being the use of a small hobbyist air compressor. These compressors use a diaphragm to generate compressed air which would address the noise issues, as a diaphragm compressor is much quieter than piston compressors. In addition to this the compressor is not required to be in immediate proximity to the haptic device which would eliminate all noise. The trigger mechanism for this method would require a 12 volt solenoid valve which would control the air flow. The use of a solenoid valve would also be extremely responsive, removing the concern of delays when firing. The primary concern of a using an air compressor is the airline that would need to be attached to the device, which may limit the devices movement. A final concern involves the health and safety of using compressed air as it can be dangerous when fired directly at the skin, particularly at high PSI (pressure per square inch), potentially causing blood clots if it enters the body. A distance of one metre would be required between the device and the participant which would ensure a safe level of dispersion meaning the air would not pose a danger. This would be very achievable providing the air dispersion issue is appropriately addressed.

The second approach utilising compressed air involves the use of air canisters which are used for fast inflation of bicycle tyres and air supplies for paintball

guns. This method would require a solenoid as a triggering switch and also a CO<sub>2</sub> cycle pump valve which would isolate the airflow. The canisters would remove any noise concerns as there is no air generation taking place and they would not require an airline. In addition to the health and safety concerns regarding using compressed air the main issue with canisters is the limited volume of air which is stored as this would cause the experience to be limited to that of the canisters volume.

After consideration of these air sources it was decided to use air canisters as they address more issues than the other air mediums. This requires the maximum amount of times the device can fire before running out of air to be calculated and adjusting the experience to reflect this.

#### **4.2.2 Base Device Prototyping**

The first stage in creating the non-intrusive haptic device involved the conceptualisation of a base structure. This would include the design of the device frame, the aiming and the firing systems. Furthermore, the components required for the air source and any potential limiting effect this may have on the aiming system needed to be considered. Two initial base designs were drawn up and reviewed regarding their feasibility, effectiveness and applicability for use with current consumer virtual reality technologies.

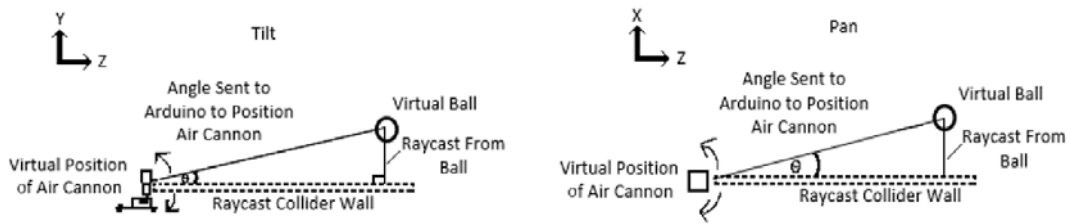
The first design involved a fairly large construction, involving a large frame which covered the width of the play area. The design would utilise a frame made from metal rods with gear teeth or cogs along the inner edges. Four stepper motors with cogwheel attachments would be used, along with four more rods attached to the frame. The centre point where the four rods intersect is where the nozzle and air delivery system would be housed. In order to position the nozzle to the correct position simple X and Y values that correspond to the physical position of a virtual object could be passed to a micro controller which would control the stepper motors. A relay module would be used to trigger the solenoid, also controlled by the micro controller, allowing a blast of air to be released.

The physical construction and software implementation of this design would be relatively simple. However, the overall design is too large and having a monolithic structure in-front of someone could be seen as intrusive. Additionally, this design would only be appropriate for study environments and unlikely that the average virtual reality consumer would readily adopt the system in a home. The tracking system also creates large accuracy tolerances as it is limited by the teeth intervals on the cogwheels and may not always hit the desired position accurately.

The second concept involves a much smaller construction with the same manner of operation as a turret. The device would be constructed from two 180 degree servo motors with a pan and tilt gimbal mount which would allow the device to target specific positions. Angles calculated from X, Y and Z values would be passed by a microcontroller in order to position these servo motors. The device would be mounted on a square steel plate which would provide a solid structural base and prevent the cannon from moving unintentionally thus avoiding the device having to be reorientated in the virtual space. The nozzle would be attached to a solenoid triggered by a relay controlled by a micro controller. This solenoid would be attached to a CO2 cycle pump valve, allowing the air canisters to be attached.

The second design which is more complex in both physical and software implementation succeeds in addressing the concerns mentioned with the first approach. This turret like design allows a more accurate targeting system in a smaller form factor. This device design would also be more likely to be adopted in a consumer virtual reality system. The primary concern with this design is the amount of weight that the servo motors can handle as the nozzle, solenoid, CO2 cycle pump valve and air canister will be housed on them. However, this can be addressed through the use of higher quality servo motors.

### 4.2.3 Virtual Object Tracking



**Figure 4.1:** Diagram showing Air Cannon pan and tilt logic.

As briefly mentioned previously, the device will aim at any set of x, y values that is passed to it through the microcontroller. The device can follow the position of a virtual object as if it was in the physical space. As illustrated in figure 4.1, the device is aimed using two simple trigonometry calculations, one each for pan and tilt. These calculations take the position of the virtual object and the position of the device in the virtual world, which is set at the beginning of each play-through. Finally, a third position is calculated by raycasting left or right from the ball's position until the collider which is projected through the centre of the play area, is triggered. Additionally, as the centre position of the servos is 90 degrees, this calculation also dictates whether the cannon subtracts or adds the resulting angle from the trigonometry calculation.

Once the game engine has completed the trigonometry calculation, the serial port will then be queried to ensure that it is not still communicating. If the serial port is clear the resulting angles will be sent for pan and tilt. If the virtual object has been blocked a signal will also be sent to trigger the cannon to fire. The micro-controller will read these values from the serial port, separate them and alter the position of the servos accordingly, as well as triggering the fire sequence if necessary.

#### 4.2.4 Control Method

In regards to the control method to be used with the experience, considerations regarding freedom and ease of use were made. From the initial study it was found that the *Leap Motion* controller would not be appropriate for a virtual reality game, with a large portion of participants commenting on its inaccurate and restrictive nature. This was due to the limited area of effect for the sensor and the requirement that the participants hands are required to be directly in front of the *Oculus Rift* at all times.

An alternative to the *Leap Motion* controller would be a custom controller; however, as previously mentioned in the impact of haptic modalities on presence chapter of this thesis the development and verification of a custom controller would be too time consuming. An additional controller option was the use of an *Xbox Kinect* which would be able to track all the key points of the body and would not require the holding of a controller. However, upon testing the *Kinect* it was found that it would often lag behind and sometimes confuse and lose body parts completely. Consequently, due to this inconsistency the *Kinect* would not be reliable enough to be used in this research.

A final option is the use of the *Oculus Touch* controllers, which are already favourably reviewed and are supported with the *Unity* game engine. The main concern with using these controllers is that in order to hold them the palm of the hand is covered which may impact on the effectiveness of the air haptics. However, as these controllers are more ergonomic to fit in a users hand and are not a wand type of controller this may complete the sensation that is suggested by the air blasts. Furthermore, most of the hand is still uncovered, which would not be the case with a custom glove controller, allowing air sensations to still be felt. Finally, the use of *Oculus Touch* controllers allow the device to be comfortable when used with commercially available virtual reality technologies in an at home environment.

## 4.2.5 Virtual Environment

Finally the virtual environment that would be used to verify the effectiveness of the haptic device needed to be considered. It was decided to create the environment with the *Unity* game engine. The virtual environment for the device needed to be a short repeatable game experience that would hold the same fidelity as a current virtual reality game.

Two concepts for this environment were initially considered; the first being a tag archery game which would allow the blasts of air to simulate being hit. The issue with this concept is the complexity that the game could reach and the amount of explanation and tutorial that would be needed. Additionally, as this research is concerned with the impact haptics have on presence, the air haptics may be seen as more impactful as the only place vibrations from the controllers would be felt is the participants hands. The second concept was a football goalkeeping game, where balls would be fired towards the participant and the blasts of air would be felt when saving these balls. This also had the potential issue of vibrations only being felt in the hands when blocking a ball. However, it was hypothesised that if a player is only given visible hands, they will not try to use other parts of their body to block the balls.

It was decided to use this goalkeeper game in the study environment as it is a more intuitive game and participants would instantly understand the mechanics upon entering the game, thus requiring little or no interference from the principle investigator. Furthermore, the goalkeeper game would be fairly short and simple to develop, more time could be devoted to polishing and making the game feel more like a satisfying VR game. Finally, the goalkeeper experience would allow for a fairer comparison between vibrotactile, air and no haptics.

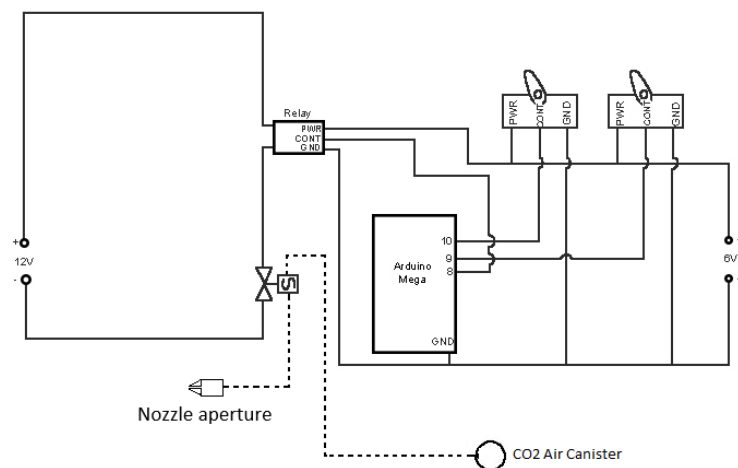


## 4.3 Implementation

Once the design was finalised, the implementation of the prototype air cannon haptic device could commence. The prototype utilised a pan and tilt gimbal which would be driven by two 180 degree microcontroller controlled servo motors. The air cannon uses compressed air stored in small air canisters, delivered via a solenoid activated by a microcontroller. The microcontroller would receive the required values to move and fire the air cannon from the *Unity* game engine via the serial connection. This section will cover how the design decisions will be implemented along with results from the beta testing of the device as well as rectifying any issues discovered.

### 4.3.1 Device Implementation

The first step towards creating the device involved the individual testing of the components ensuring that they all worked. This was carried out by using a breadboard and an *Arduino Mega* microcontroller, this initial component testing was carried out without an air canister attached. However, the operation of the solenoid could still be confirmed as the movement of the valve could be heard and felt when it was triggered. Once all the components were confirmed operational a wiring diagram (figure 4.2) was created which could be used for reference during the final construction.



**Figure 4.2:** Air cannon schematic (V1).

In order to ensure the device would not move unintentionally during operation, a heavy and sturdy base was required. To create this base, four feet were attached to a steel plate and temporary markings made to plan out the positioning of the other components (figure 4.3).



**Figure 4.3:** Solid base for Air Cannon components.

In order for the cannon to be able to aim, a simple two DOF tilt and pan gimbal typically used in robotics was used. The gimbal utilised two 180 degree servo motors that would be controlled by a microcontroller to allow for the required field of movement. This gimbal construction (figure 4.4) would then be used as a platform, holding the air delivery system.



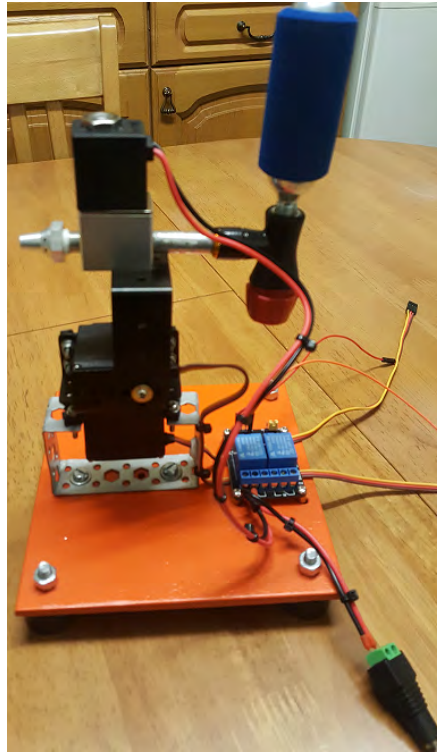
**Figure 4.4:** Pan and tilt gimbal construction.

The final system to be constructed was the air delivery system comprising of: a solenoid, nozzle, CO2 air canister, cycle tire valve and an *Arduino* relay module. A relatively low power solenoid was selected only requiring 12 volts; however, this was still more than a microcontroller could supply. To address this a relay module and an external 12 volt plug was used which successfully powered the solenoid. The powered solenoid provided control over how much air was released on each activation. In order to attach the cycle tyre valve which housed the CO2 air canister, a double threaded  $\frac{1}{8}$  inch air pipe was attached to the solenoid using PTFE tape in order to seal the thread against air leakage. To complete the air delivery construction a nozzle was attached, a safety nozzle was selected which would redirect air to smaller exhaust apertures should the main aperture be obstructed, the nozzle was also attached using PTFE tape.



**Figure 4.5:** Complete air delivery system construction.

The final process regarding the implementation of the air device required the air delivery system and gimbal construction to be mounted onto the base plate. Upon completion of the construction, simple tests could be carried out ensuring the device operated as required.



**Figure 4.6:** Complete air cannon construction.

### 4.3.2 Unity to Arduino Implementation

Before any low level testing could commence a system had to be created which would allow the *Unity* game engine to communicate with the microcontroller. In order for the game environment to transfer positions of the tracked objects a custom plug-in was produced, which has been publicly released and is available as open source software. It was decided to create this plug-in to aid any future *Arduino* to *Unity* projects. In tutorials that are currently available achieving the same effect can be hard to follow and other plug-ins available on the *Unity* store were expensive or lacking in features.

The plug-in introduces a set of ten functions which enable easy serial communication between the *Unity* game engine and an *Arduino* product. The

plug-in allows a user to find multiple devices connected to the computer and establish or end individual connections, the devices can then be written to and read from. An *Arduino* sketch is included in the open source version which allows the user to identify devices if multiple are connected. The sketch also allows users to test the connection, set, control and get the current state of any pin on connected devices from the *Unity* engine without requiring users to write their own sketch.

As the use case in this research was complex a new sketch was created which would parse a string of data passed to it. This string of data would hold the two pan and tilt angles which would position the servos; additionally, a value for the cannon to fire a blast of air is also sent with this string. A handshake system was also implemented which allowed the *Arduino* to read new values when it was ready and the *Unity* game engine to not send more values than could be handled. This kept the serial connection clean preventing any unexpected movements that could occur as a result of the micro-controller partially handling values.

### **4.3.3 Initial Device Beta Testing**

With the construction of the device complete and a system in place allowing the communication between *Unity* and the microcontroller the initial beta test could begin. This test utilises an *X-box Kinect* which was used to track the right hand of participants, the position was then be calculated and the angles passed to the device which tracked the participants hand. A blast of air would be fired periodically, after which the participant would identify when and where they felt the blast.

### **4.3.4 Beta Test Findings**

The beta test was conducted with five participants and highlighted a number of significant concerns with the device. The first issue which was discovered was the lack of accuracy and unreliability of using the *Kinect*. However, this was not

seen as a significant issue as this test was assessing the device, the *kinect* would not be used for the final experience as previously explained in the design section of chapter four. One expected issue, highlighted in the related literature, was confirmed during the beta test, this was the fast dispersion rate of the air. One way of addressing this issue was by increasing the volume of air that was stored, as the current amount of air was limited by the size of the canister. Additionally, the nozzle aperture could also be adjusted which would shape the air aiding the travel distance. The primary issue was the use of canisters, not only do they not store a large volume of air, limiting the air travel distance, but the pressure in the canister is not consistent. When the first blast of air is released the pressure is lowered significantly, reducing the travel distance and the overall sensation of the air.

#### 4.3.4.1 Aperture Selection



**Figure 4.7:** Tested nozzle apertures.

In order to address the air dispersion rate, as well as provide the correct sensation, the nozzle of the cannon had to be changed. A total of four different aperture styles were tested as seen in figure 4.7. Two of which were custom made in an attempt to shape the air into a vortex, Which would assist the distance the air can travel by folding it in on itself providing some self propulsion.

The original aperture was too small and forced the air to disperse extremely quickly in a wide cone. The second and third apertures were custom made and extremely experimental using various techniques to create a vortex. Some success was made with these apertures in terms of range and sensation, it became obvious that without professional machining the creation of a vortex utilising a custom aperture and compressed air would be difficult. This is because the air is moving very quickly making curving and manipulating the air into a vortex a very complex task.

The fourth aperture utilised holes on the body of the nozzle introducing the venturi effect, which provided reliable range and an appropriate physical sensation. The compressed air created suction as the high pressure air passed through the nozzle and the holes, the surrounding air was pulled through adding additional force. This shapes the air blast so that it hits the player before it disperses.

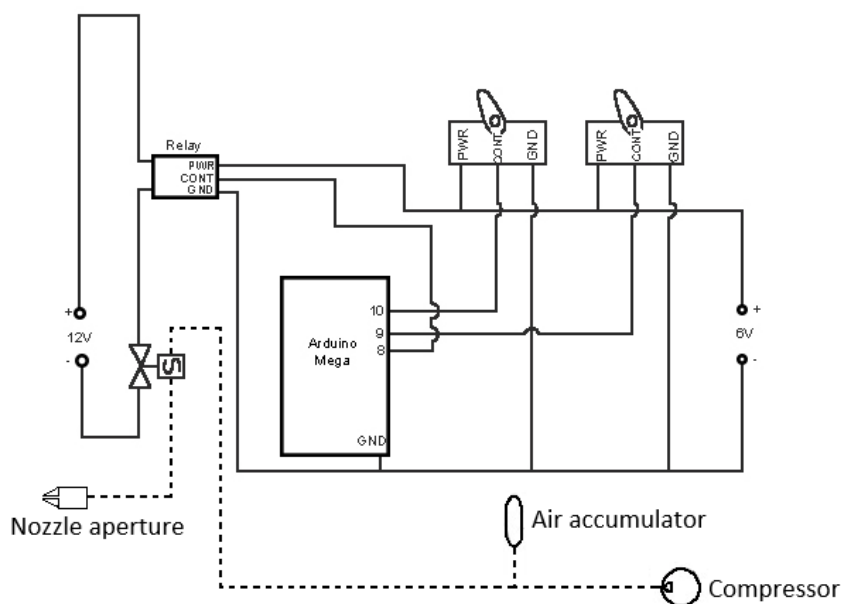
#### **4.3.4.2 Addressing Air Range**

Addressing the range that the air could reach without being too weak upon reaching the user, required a fairly significant redesign of the device. The first step to remedying the issue was the replacement of the CO<sub>2</sub> canisters with a hobbyist air compressor. After the beta test it was clear that the CO<sub>2</sub> canisters would not supply a consistent sensation or hold enough air, the introduction of the compressor increased the effective range. As mentioned in the design section of chapter four the use of an air compressor came with its own limitations, such as noise and the potential restrictive nature of requiring an airline attached to the device. However, precautions such as moving the compressor and requiring participants to wear sound cancelling headphones would address the noise issue. Furthermore, if a diaphragm compressor could be used the level of noise and vibrations would be minimal. Regarding the airline, an extremely flexible braided airline was tested and found to not restrict the movements of the servo motors.



**Figure 4.8:** Air accumulator.

The use of an air compressor only addressed the consistent pressure issue from the air canisters, the volume of air was still limited to the air stored in the airline. To achieve a greater distance a greater volume of air was required, to solve this an air accumulator, also known as an air receiver, was built. The accumulator was relatively easy to build, as it is simply a strong hollow pipe capped at both ends with a hole allowing the air to enter and exit, as seen in figure 4.8. The air continues to be generated until both the airline and the accumulator were at maximum capacity. This makes a greater amount of air available to be forced out of the aperture upon activation of the solenoid causing the air to travel a greater distance. This redesign of the device also prompted an update of the wiring diagram as seen in figure 4.9 below.



**Figure 4.9:** Final system schematic.



### 4.3.5 The Final Air Cannon

Following the redesign of the device, a second beta test was carried out to verify the effects of the redesign. As it was strongly believed the *Kinect* was causing issues with the device's tracking, therefore requiring the need for a redesign and test. This test utilised the *Oculus Touch* controllers and involved the tracking of the left controller, again periodically firing at the participant's right hand. A significant improvement was observed during this second test, with the device successfully tracking the *Oculus Touch* controller and air blasts being able to be felt a minimum of a metre away.

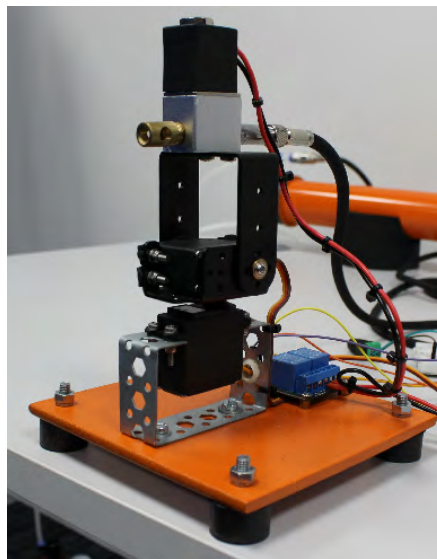


Figure 4.10: Air cannon with Venturi Effect aperture.

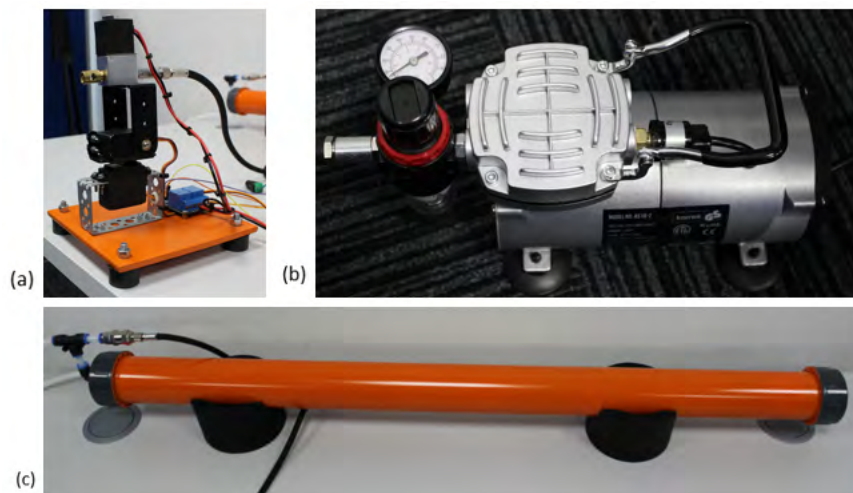
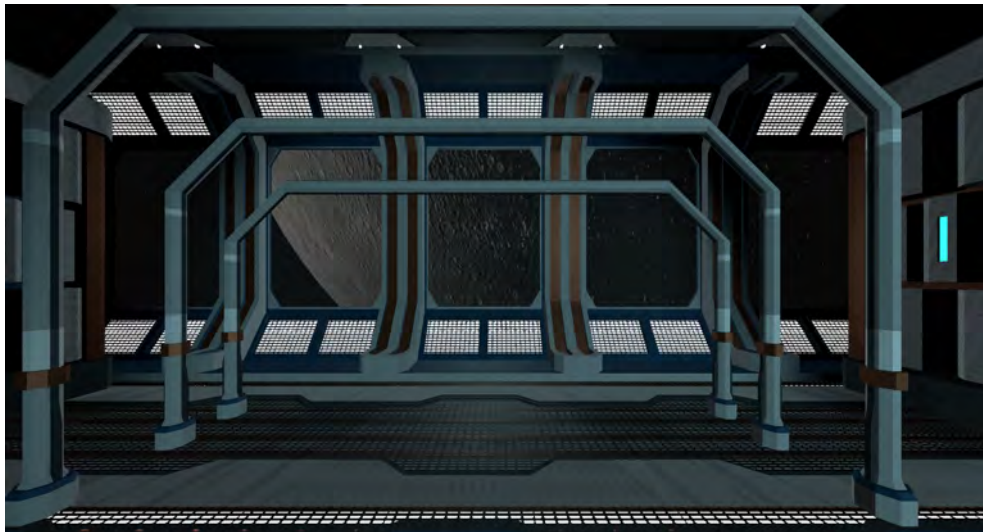


Figure 4.11: (a) Air cannon prototype. (b) Hobbyist air compressor. (c) Air accumulator.

### 4.3.6 Virtual Environment Implementation

With the device constructed and operating as desired the virtual reality game which would be used for the study had to be created. As previously discussed in the design section of this chapter the game would be a goalkeeping game. This is to mimic a game that may be typically purchased to play in virtual reality, assisting in the removing of the in lab experiment feel which may impact results.

To achieve a quality looking game, a futuristic texture pack was used to create and furnish the virtual room. Additionally, a planet sky box which enabled the room to contain windows, lessening the claustrophobic feel of the room was used. To avoid the game feeling overly artificial, the lighting was adjusted to add some atmosphere to the room as seen in figure 4.12.



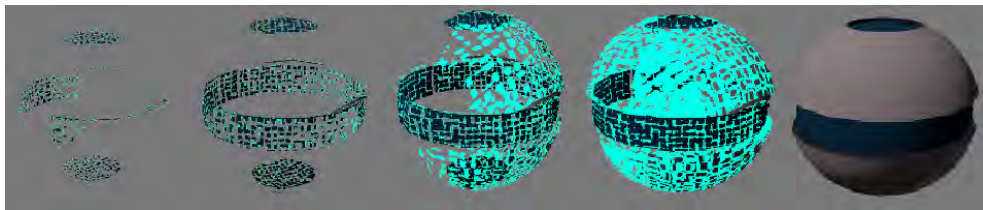
**Figure 4.12:** In game goal and view from windows.

At the far end of the room a cannon model was placed where the balls would be fired from. A system was created to fire the balls at random intervals and with a random force within two adjustable tolerances. The time interval was adjusted according to the compressors recharge time so the air system would not be drained too quickly which would cause sensations to become inconsistent. In addition to this the cannon would also point to a random location within the goal each time it fired. The cannon would visibly point to a new position 0.5 seconds before firing allowing participants time to notice the new target area.

Finally, a system was created which introduced a “phase in” effect on the ball, as seen in figure 4.13 and 4.14. The intention for this was to add a further level of difficulty as the ball would start the “phase in” effect upon firing and wouldn’t be completely visible for one second after firing. Furthermore this effect also added to the quality and polished look of the final game.



**Figure 4.13:** Ball phase in effect as it travels towards the player.



**Figure 4.14:** Ball phase in effect.

A goal was positioned behind the player, this goal used colliders to detect when a ball was not blocked after which score calculations would be applied. To avoid any potential injuries of participants jumping or rushing and tripping over wires, the size of this collider was adjusted according to the participant’s reach. The goal size was adjusted at the start of the experience by asking the participant to perform two tasks. The first task required a T-pose to be performed (figure 4.15), which would size the goal according to the position of the controllers once the pose was completed. The second task involved touching the nozzle of the air cannon which would indicate the position of the cannon in virtual space (figure 4.16), this was required to allow the cannon to could accurately track the ball. As the same environment would be used for air, vibrotactile and no feedback participants were required to touch the nozzle for every condition to avoid any potential impact on

the results. Upon both of these tasks being completed successfully a three second countdown would start before the game commenced, an additional five minute timer started counting down, indicating the end of the game session.



Figure 4.15: T-pose task.



Figure 4.16: Touch nozzle of air cannon task.



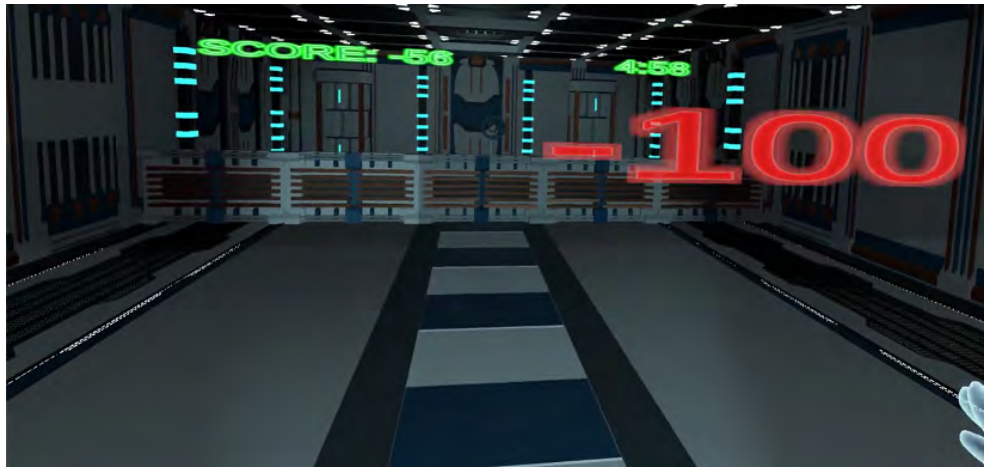


**Figure 4.17:** Task successfully completed feedback.

Finally, in order to complete the game experience some arcade like sound effects and a score mechanic was added. The sound effects indicated the blocking and missing of a ball as well as the addition and subtraction of points. In addition to these sound effects background music was added further adding to the arcade like feel and quality of the game. Additionally, the background music masked the low amount of noise created by the air compressor. The score mechanic simply added 100 to the participants total score upon blocking a ball (figure 4.18) and subtracted 100 upon missing a ball (figure 4.19). A bouncy effect was added to the score text in order for scores to match the game's aesthetics. It was decided to implement a scoring system as the results could be recorded and be used as further support to any conclusions gathered.



**Figure 4.18:** Ball successfully blocked, starts the phase out despawn effect and score points added feedback.



**Figure 4.19:** Ball missed by player and score points subtracted feedback.

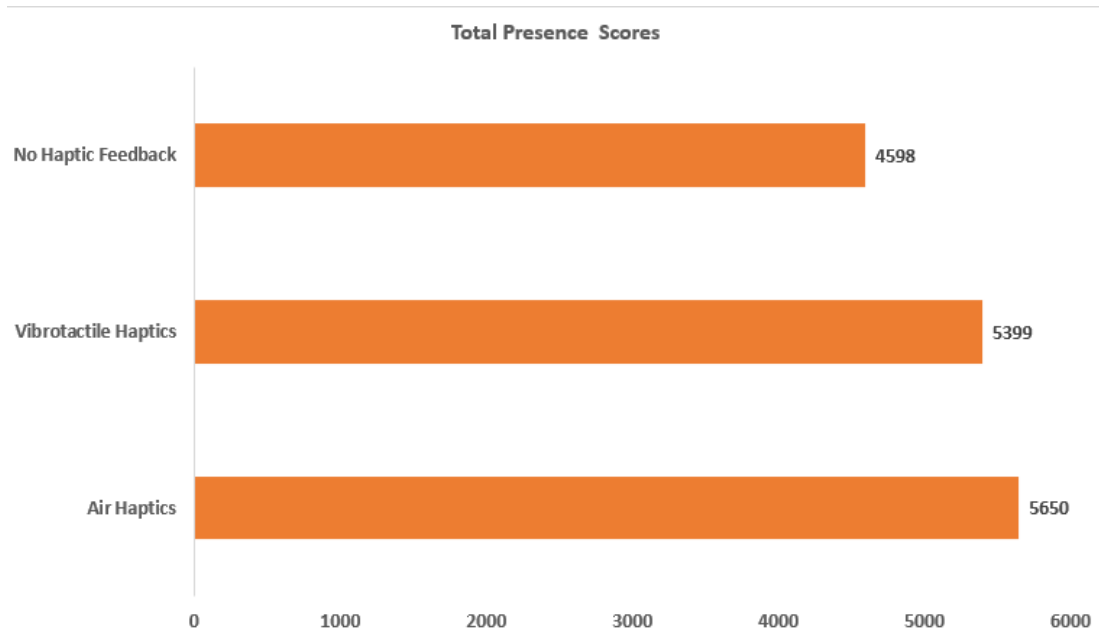
## 4.4 Results

This study utilised the Witmer and Singer presence questionnaire (see appendix A) as well as an additional custom questionnaire made to compare the three haptic experiences (see appendix B). The maximum presence score which indicated to the best experience of presence is 154. These questions each relate to certain sub categories of: realism, possibility to act, quality of interface, possibility to examine, self-evaluation of performance and haptic sense. In order to gain a total presence score per participant from the questionnaires, scores from questions 14, 17 and 18 were reversed and added to the sum of the remaining questions. All of the final presence scores were then totalled together in order to achieve a single total presence value, this process was carried out all three conditions (air haptics, vibrotactile haptics and no haptic feedback), resulting in three summed up presence values for each participant. For each participant the condition order was advanced by one in an 'A, B, C' style with 'A' representing air haptics, 'B' vibrotactile haptics and 'C' no haptic feedback. For example the first participant would undergo the study in the 'ABC' order meaning the order of haptic experience would be air, vibration and none. The following participant would have the order of 'CAB' resulting in the order of haptics being, no haptics, air and vibration, the order looped in this way throughout the study to prevent an order bias.

The study was run for a total of three weeks with 42 participants, of these participants 69% (29) were male and 31% (13) were female. The participants had a median age of 22 (mean of 24).

The overall presence scores of each condition ( air haptics, vibrotactile haptics and no haptic feedback) were compared using a one way repeated ANOVA test and the Bonferroni correction. There was a significant effect of presence values when using the air cannon haptic device,  $F(2, 123) = 57.78$ ,  $p = < 0.001$ , effect size = .48. Using the air cannon haptic device consistently increased the participants presence scores compared to using vibrotactile feedback and no haptic feedback at all.

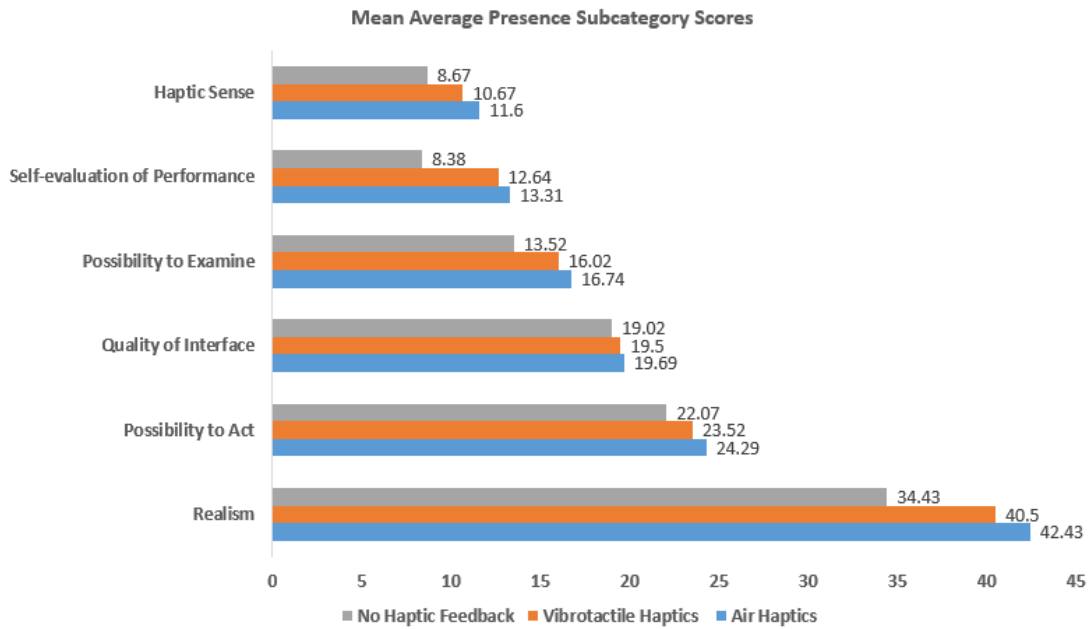
Post hoc comparisons using the Bonferroni correction revealed that when comparing presence scores from air haptics with vibrotactile a mean difference of 5.97, 95% CI [.07, 11.88], was statistically significant,  $p = 0.046$ . When comparing presence scores between air haptics with no haptic feedback the test revealed a difference of 25.04, 95% CI [19.14, 30.95], was also statistically significant,  $p = < 0.001$ . Finally the test also revealed, when comparing presence scores between vibrotactile and no haptic feedback a difference of 19.07 95% CI [13.16, 24.98], which was statistically significant,  $p = < 0.001$ . The Bonferroni correction is typically applied by dividing the desired alpha level by the number of comparisons then using that number as an adjusted p-value to determine statistical significance. Since the results in this study were analysed by using the “SPSS” software by IBM [125] the correction is applied slightly differently. “SPSS” applies the Bonferroni correction by taking the uncorrected p-value and multiplying it by the number of comparisons made, leaving the p-value for determining statistical significance as 0.05.



**Figure 4.20:** Graph comparing the total presence scores for all three conditions.

Figure 4.20 shows the total presence scores for the three conditions of the study. This graph shows there is a large difference between the no feedback condition and the two with feedback. Additionally, a small increase can be seen between the vibrotactile and air haptics conditions. Figure 4.21 displays the mean average presence scores for the questionnaire subcategories. These results show a clear difference between the conditions particularly in the haptic sense and realism categories. The significance values and mean differences for each of these subcategories are shown in table 4.1.



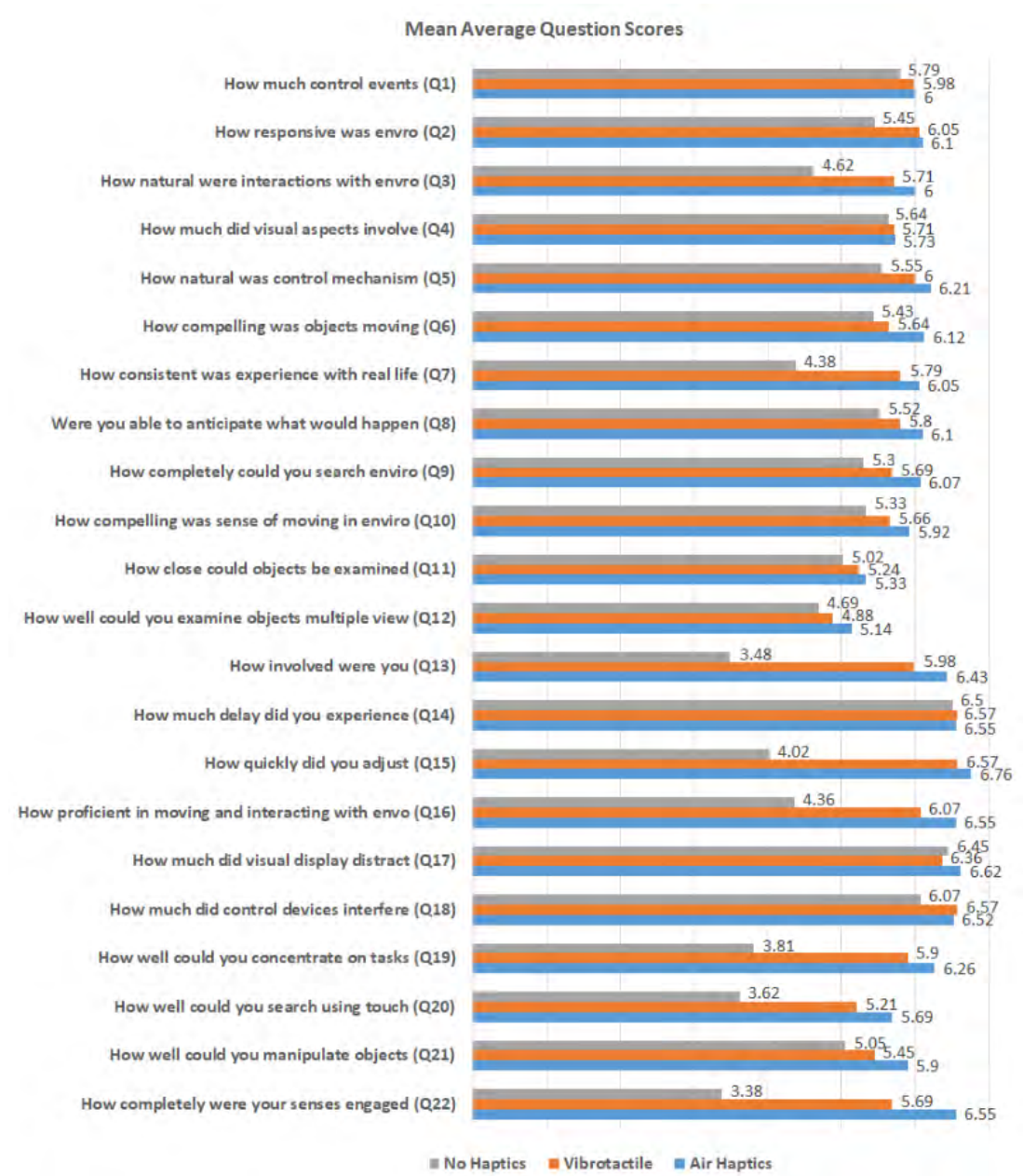


**Figure 4.21:** Graph comparing the mean average presence subcategory scores for all three conditions

Subcategory	Significance (p value)
Haptic Sense	<.001
Self Evaluation of Performance	<.001
Possibility to Examine	<.001
Quality of Interface	.012
Possibility to Act	<.001
Realism	<.001

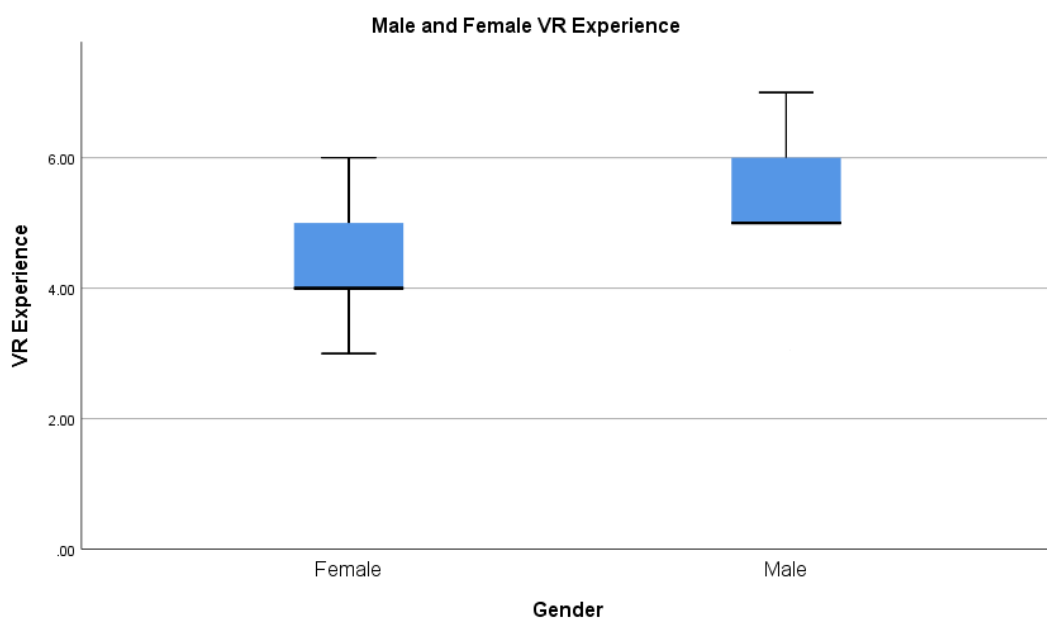
**Table 4.1:** Table showing the significance scores from repeated ANOVA test for each subcategory.

Figure 4.22 shows the mean average scores for each question for all three conditions of this study, displaying a clear trend in lower scores for the no haptic feedback condition. Scores for the air haptics condition are also consistently similar or higher than the vibrotactile condition. A number of these questions show large differences between the conditions. Some of the most noteworthy differences which will be covered further in the discussion section of this chapter are questions: 1, 3, 7, 13, 14, 15, 16 and 19.

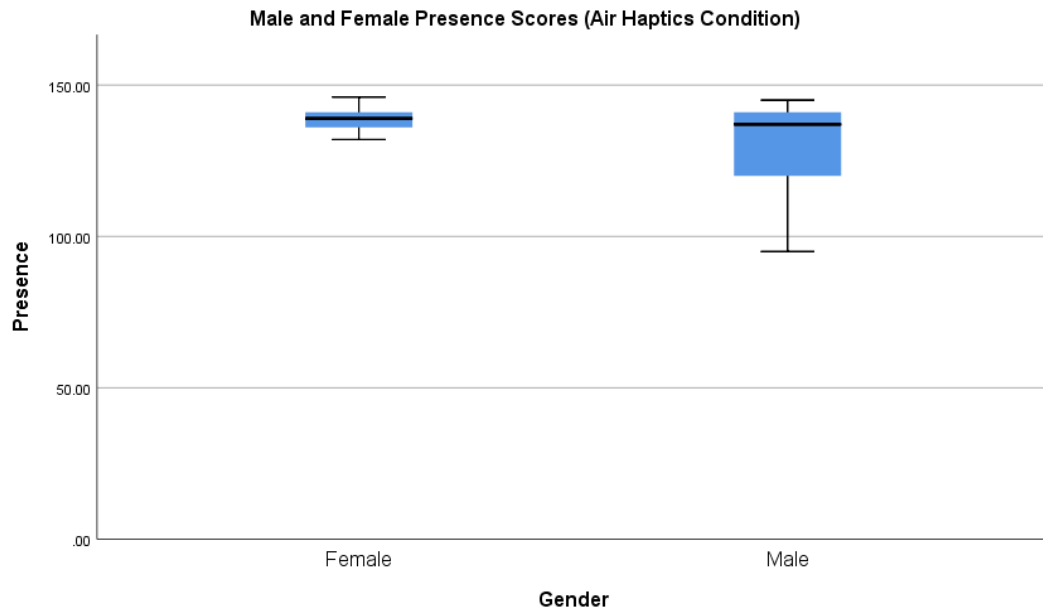


**Figure 4.22:** Graph comparing the mean average scores for each question in the presence questionnaire between the air, vibrotactile and no feedback conditions (with questions 14, 17 and 18 reversed).

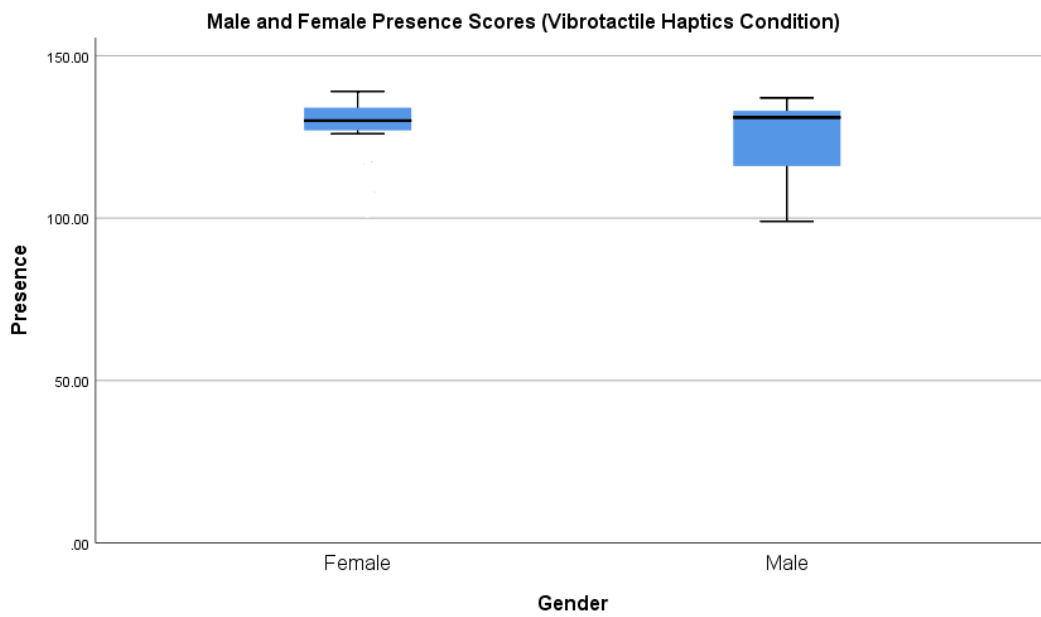
As in the first study participants were asked to score themselves on their virtual reality experience on a 1-7 point Likert scale. Both the female and male virtual reality experience alongside their presence scores can be seen in figures 4.23 - 4.26. Due to an uneven sample size between male and female participants a random sample of the higher sample size. The graphs show that the impact haptics may have had on presence was not gender dependent, with the majority of presence scores grouping together according to the haptic condition. Additionally these illustrate that the the participants virtual reality experience also did not impact the results as participants with low virtual reality experience kept in the trend of scores given by those with high experience.



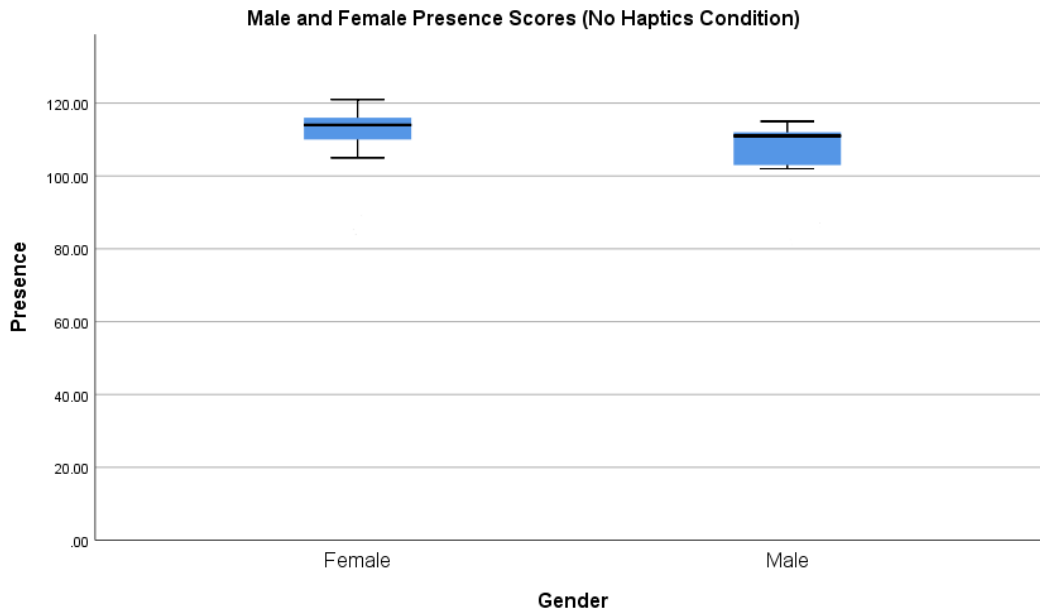
**Figure 4.23:** Graph comparing the male and female VR experience scores.



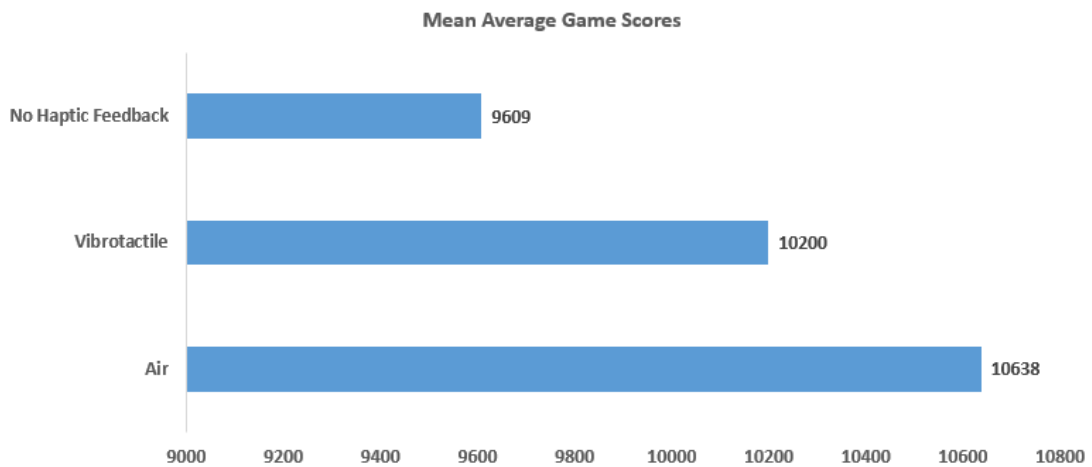
**Figure 4.24:** Graph comparing the male and female presence scores for the air haptic condition.



**Figure 4.25:** Graph comparing the male and female presence scores for the vibrotactile haptic condition.



**Figure 4.26:** Graph comparing the male and female presence scores for the no haptics condition.



**Figure 4.27:** Graph comparing the mean average game scores for all three conditions

Participants game scores were logged upon the completion of each five minute play through for each condition. Figure 4.27 shows a slight increase using air haptics when compared with the vibrotactile condition and a significant increase from the no haptic feedback condition. These results show that the air haptics does not inhibit or distract participants from the experience; furthermore, they suggest a slight increase in player performance.

Preferred Haptic Method Questionnaire Results

Question	Response	Tally	Total
I enjoyed playing the game more with:	Air	### ### ## II	17
	Vibration	### ### ### ### III	23
	No air or vibration		0
	No Preference	II	2
I found it more comfortable to play with:	Air	### ###	10
	Vibration	### ### ### ### ### IIII	29
	No air or vibration		0
	No Preference	III	3
I felt more immersed in the game with:	Air	### ### ### ### ### ### III	33
	Vibration	### III	8
	No air or vibration		0
	No Preference	I	1
I felt uneasy with:	Air	### I	6
	Vibration		0
	No air or vibration	### ### ### ### ### III	28
	No Preference	### III	8
I felt more skilful with:	Air	### ### ### ### II	22
	Vibration	### ###	10
	No air or vibration	###	5
	No Preference	###	5
I felt more frustrated playing with:	Air	I	1
	Vibration	I	1
	No air or vibration	### ### ### ### ### ### II	32
	No Preference	### III	8
I felt more engaged playing with:	Air	### ### ### ### ### IIII	29
	Vibration	### III	8
	No air or vibration		0
	No Preference	###	5
I had to concentrate most playing with:	Air	### IIII	9
	Vibration	III	3
	No air or vibration	### ### ### ### I	21
	No Preference	### IIII	9
I felt more challenged while playing with:	Air	### IIII	9
	Vibration	###	5
	No air or vibration	### ### IIII	15
	No Preference	### ### III	13

Figure 4.28: Frequency table showing the results from the comparison questionnaire.

### Preferred Haptic Method Questionnaire Average (mode) Results

Question	Average Response (mode)	Resulting Haptic Feedback
I enjoyed playing the game more with:	1	Vibrotactile Haptics
I found it more comfortable to play with:	1	Vibrotactile Haptics
I felt more immersed in the game with:	2	Air Haptics
I felt uneasy with:	3	Without Air or Vibrotactile Haptics
I felt more skilful with:	2	Air Haptics
I felt more frustrated playing with:	3	Without Air or Vibrotactile Haptics
I felt more engaged playing with:	2	Air Haptics
I had to concentrate most playing with:	3	Without Air or Vibrotactile Haptics
I felt more challenged while playing with:	3	Without Air or Vibrotactile Haptics

**Figure 4.29:** Table showing the average (mode) results from the comparison questionnaire and the resulting haptic feedback.

Results from the custom comparison questionnaire (see figure 4.28 and 4.29) show that participants disliked the no haptic feedback condition. This indicated that they felt uneasy and they had to concentrate more when playing without haptic feedback; additionally, it is shown that they considered the game more challenging without haptic feedback. This could be a benefit in some scenarios; however, this can be disregarded as it is also reported that participants felt the most frustrated in this condition. Participants indicated that it was more comfortable and enjoyable to play with vibration haptics which was expected as vibrotactile haptics are common in video game technologies. Finally, participants reported feeling more immersed, skilful and engaged with the game when using the air cannon haptic device over the other haptic conditions.

As previously mentioned in the methodology section in this chapter, video recordings were taken of the play throughs to be used for observational data. Whilst these recordings did not show anything significant it was observed that the

large majority of participants were viewed swinging hands and generally looking around only in the no haptic feedback condition. This strongly suggested that participants become bored and uninterested without any haptic feedback.

## 4.5 Discussion

The results from this study indicated that a higher fidelity haptic feedback had a positive impact on not only presence but also on the way players perceived their performance. As expected the no haptic feedback condition resulted in the lowest presence scores. The presence scores were marginally higher in the air haptics condition than the standard vibrotactile condition. This result showed the non-intrusive haptic device was successful in improving presence levels in a video game environment.

Breaking down the presence questionnaire into its subcategories showed the haptic sense for air haptics was significantly higher than the vibrotactile condition. Furthermore, the realism subcategory strongly suggested that the device was successful in delivering a satisfying tactile feedback. Interestingly, the self-evaluation subcategory suggested that a lack of haptic feedback caused players to believe they were performing poorly. However, in the air haptics condition players viewed their performance positively even more so than when playing with vibrotactile feedback. Finally, the quality of interface subcategory showed very little difference in scores between the three conditions. This could suggest that the set up required by the air haptic device was an annoyance to some; however, as the vibration condition was rated in the same way this was most likely not the case. Alternatively, this could be a positive aspect as the device is seen as a similar level of inconvenience as vibrotactile haptics and could indicate that the design of the device has succeeded in making it non-intrusive.

As suggested in the analysis of the initial study results the presence and overall game experience did not seem to be affected by gender or virtual reality experience. This was proven by a trend being followed showing consistent scores with no



notable differences for all of the haptic conditions regardless of their gender or virtual reality experience.

The games scores for each participant in each condition were logged upon the completion of each five minute session. These scores showed that on average participants scored higher in the air haptics condition and lowest in the no feedback condition. This supports the previously mentioned self-evaluation of performance results, suggesting that participants do perform worse without haptic feedback. The reason for this could be due to the participant becoming uninterested in the game once tactile feedback had been removed, as observed in the video recordings. Regarding the high scores seen in the air haptics condition there was strong evidence to suggest that this was due to participants being able to fully concentrate and become involved in the game as the air haptics made it a more complete experience. Evidence for this can be seen from the results of questions 13 ( How involved were you in the experience? ), 15 ( How quickly did you adjust to the experience? ) and 19 ( How well could you concentrate on the experience? ) which contribute to the self-evaluation of the performance subcategory. In addition to this, a small number of participants were captured by the video recordings verbally expressing how much easier it was to focus during the air haptic condition. Finally, these logged scores suggested that the new haptic device did not inhibit or distract participants from playing the game, further satisfying the final research question of this thesis.

The mean differences for some of the questions of the presence questionnaire (shown in figure 4.22) provide an interesting insight into what effects the different haptic experiences had on the participants presence. The mean differences of the first question (How much were you able to control events?) were very small. This indicated that participants felt they did not lose any control whether haptics are different or completely removed. As expected results for the second question (How responsive was the environment to actions that you initiated (or performed)?) suggested participants felt the environment was unresponsive when haptic feedback was removed whilst in the air condition the environment was more responsive. This also held true for question three (How natural did your interactions with the environment seem?), which indicated the air condition made the environment feel

more natural. This implied the device successfully delivered satisfying feedback. For question seven (How much did your experiences in the virtual environment seem consistent with your real world experiences?), further support that the device delivered a satisfying feedback.

Results for question 13, seen in figure 4.22, (How involved were you in the virtual experience?) participants consistently indicated that they felt more involved with the experience when using air haptics. Results from question 14 (How much delay did you experience between your actions and expected outcomes?), indicate that the delay participants expected between touching the ball and the tactile feedback received was similar to that of the vibrotactile condition. This implied the device was successful in delivering feedback and any blasts of air that may have been mistimed were unnoticed. Question 15 (How quickly did you adjust to the virtual experience?), suggested that participants had greater difficulty adjusting to the no haptic feedback condition. Results from this question also indicated that participants adjusted faster to the air haptic condition, implying that the feedback did not feel alien. This could be due to the sensation matching real life experiences enough for it to feel natural, as suggested by results from question seven. Finally, results from question 16 (How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?), indicated that participants felt more proficient when playing the game with air than with vibration. Furthermore, the no feedback condition caused participants to feel significantly less proficient, which was also supported by the logged game scores. Question 16s results are also supported by question 19 (How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?), which indicated participants struggled to concentrate on the game without feedback. Whilst in the air haptic condition, results indicated participants felt it easier to concentrate on the experience.

Results from the custom comparison questionnaire support the common theme throughout this discussion section, being the dislike towards the no haptic condition. The responses taken from this form indicated that participants felt uneasy and that they had to concentrate more as well as viewing the game as more

challenging without the feedback. Whilst in some scenarios this discovery could be used in the creation of interesting game design techniques to further increase difficulty. However, this was not a desired aspect of the game in this study; additionally, participants also indicated that this condition made them frustrated. Results from this questionnaire indicated that the majority of participants enjoyed and felt more comfortable in the vibrotactile condition. Of course this was expected as vibrotactile haptics are extremely common not only in games but also in day to day usage of a mobile phone causing the sensation to be much more accepted. Finally, participants reported feeling more immersed, skilful and engaged in the air haptics condition then with the other haptic methods, which was supported by results from both the logged game scores and the presence questionnaire.

#### **4.5.1 Device Limitations and Improvements**

Our results suggested a promising approach to non-intrusive haptic feedback. In this section we provide additional detail and insights post study period which could improve future iterations or inspire new non-contact haptic devices.

#### **4.5.2 Multi Directional Air Blasts**

In the air cannon implementation section of this thesis the pan and tilt servo configuration was discussed, with the air cannon unit itself being relatively compact and designed with being used by a typical consumer in a living room. It is expected that the cannon will always be placed on a table around 0.5 meters from the ground. Upon further consideration it is obvious that this creates a mono directional experience with blasts of air always coming from the same central position.

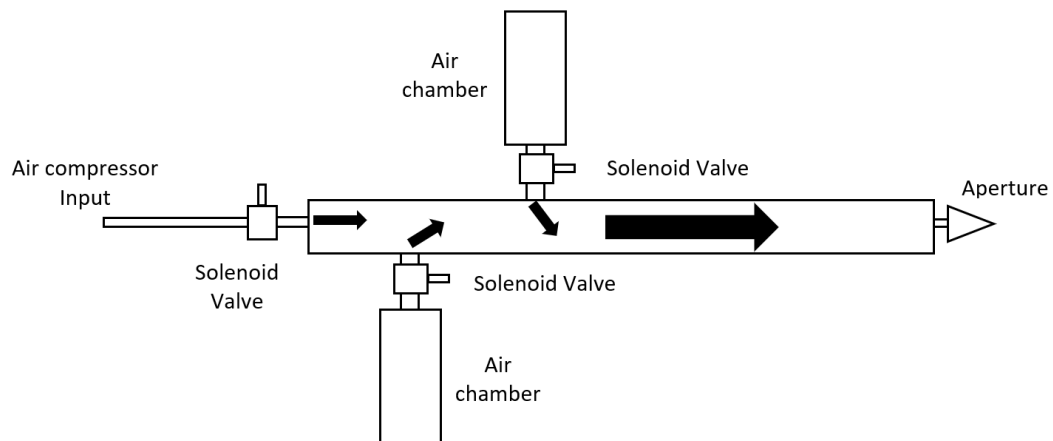
The considered solution to this is a fairly complex one involving attaching the cannon to a two point pivoting arm. This would allow the cannon to operate in the same way however with the added dynamic of being able to more accurately replicate the sensations directional source as is experienced in real life. Further

investigation and consideration would be needed to fully realise the potential effects that such an adaptation would have on the system as a whole.

### 4.5.3 Aperture Array

With consideration towards the single aperture used in this study an interesting advancement on the cannon introduced in this thesis would be a similar solution but hosting an array of nine or more apertures. A configuration like this would be able to more accurately replicate forceful sensations, over a longer distance. In addition to this there is potential for creating the illusion of a shape by firing air through certain apertures in a sequence. If this was also to be teamed with visual suggestion provided by virtual reality a very effective delivery method of targeted haptics could be created.

### 4.5.4 Multi Air Chamber Configuration



**Figure 4.30:** Diagram displaying a potential configuration for a multi air chamber air cannon.

Due to the fast dispersion rate of air, range and force will be a persistent issue when using an air powered haptic system. Whilst this was somewhat addressed in this thesis a potential alternative method that would increase the range and power of the device would be to use multiple air chambers and valves. As seen in

figure 4.29 this device would have a long tubular nozzle between two air chambers flowing into it controlled by separate solenoids, in addition to the air compressor air source. Once the air compressor solenoid is activated the two air chamber solenoids are then activated in quick succession, which would provide additional force behind the initial burst of air. This could also be improved with a venturi effect aperture similar to the one used in this thesis. This solution should provide better range and force, the main issue with the solution would be timing the solenoid valves to release within micro seconds of each other, which would require a large amount of testing.

#### **4.5.5 Sound Produced During Operation**

The sound produced by not only the cannon firing but also the charging of the air compressor is significant. Whilst in the study this was mitigated through the use of sound cancelling headphones and the games' music, more can be done to absorb this noise. For example, noise dampening foam can be used to surround the air compressor as well as placing the compressor on an vibration absorbing platform. However, as the participant would be moving around in order to play the game and the vibration from the compressor is very light, this was not deemed necessary. Furthermore, an advantage of using a compressor is that it is not required to be in the same room as the rest of the system. Alternatively, this noise and light vibration could be taken advantage of by game designers as a potential additional dimension to a game experience.

# Chapter 5

## Conclusions

The purpose of this chapter is to provide a brief summary of the thesis and a detailed discussion of the research as a whole. Specifically, this chapter intends to satisfy the final objective detailed in the introduction of this thesis, critically analyse and discuss the feedback device and results.

This discussion also highlights the relevance of the findings and how they are related to the research questions of this thesis. Another purpose of this chapter is to highlight the limitations of this work and discuss where it could be extended in the future.

This chapter starts by firstly summarising the content of this thesis, then discussing what was achieved throughout the work. Following this, the results found are related back to the research questions of this thesis. The limitations are then addressed and areas of future work is identified.

### 5.1 Thesis Summary

This thesis firstly introduced the topic of haptic feedback with virtual reality and discussed the use and current state of haptic feedback in video games. A review of the related literature was conducted, which outlined research surrounding haptic feedback and limitations surrounding various methods of haptic feedback. Following this, a study was carried out in order to establish whether different tactile sensations impact presence in a meaningful way. This study involved two

groups of participants handling various physical objects with varying textures, shapes, sizes and weights whilst in virtual reality. Results from this initial study indicated that haptic feedback does have a meaningful impact on presence and provided insight into what haptic modalities caused this. The study also highlighted the importance of the non-intrusive factor and the direction towards using air as a medium for the haptic device, which was supported by the literature.

Using results found from the first study a haptic device was then conceptualised and designed to use air as the haptic medium. This device operated on a similar principle as a turret, being able to aim using a gimbal and two servo motors. Upon the creation of the device multiple short beta test studies were carried out in order to verify that the device operated as expected. These beta tests allowed the identification of various issues relating to the power and range of the device due to the use of air. The findings prompted a minor redesign of the device in order to achieve the desired feedback. Following this, a study was carried out in order to verify that the device could create satisfying feedback and that participants felt that it was non-intrusive. This study involved participants playing a goalkeeping game three times with different haptic experiences, air, vibration and no feedback. The results also indicated how the air haptic device compared to no feedback and the standard vibrotactile feedback. The results from this study showed participants preferred the air haptic device and the feedback created was satisfying, validating the effectiveness of the approach, suggesting that haptics do not need to be intrusive or particularly extravagant to be effective.

## 5.2 Discussion

With the initial study of this research it was identified that object properties have a meaningful impact on presence in a virtual reality environment. It was suggested that certain object properties such as shape, size and obvious texture were the most noticeable, meaning subtle texture changes and weight as having the least impact on presence. This study also suggested that a users mind would not fill in the disconnect that participants felt when they experienced something that

was not being visually perceived. However, in the second study this was found to be false as the results indicated the mind would bridge the disconnect or at least add to the experience when an indication of tactile feedback was supplied, such as a blast of air with a ball coming into contact with the hand. This indicated that the participants' mind would bridge the disconnect providing it is not too obvious. These findings satisfy the first research question: what impact do certain object properties have on presence within a virtual reality environment? Will a users mind bridge the disconnect, when something is physically experienced that is not visually perceived and visa versa?

The air haptic device introduced in this thesis also addressed some issues regarding the use of air as a haptic medium found in the literature. During the review of related literature Tsalamlal et al mentioned air as being a promising method of haptic feedback, but is limited due to the deliverable distance [72]. Whilst the deliverable distance of air was an issue encountered in this research it was addressed by adding an air accumulator to add more volume to the system. In addition to the accumulator an aperture which utilised the venturi effect was used, which raised the deliverable distance of the air to an appropriate range for use in this research.

Throughout the design of the air cannon it was aimed to keep the device relatively compact so it could be readily integrated into a consumers virtual reality set up. As previously mentioned issues identified in beta tests of the device caused a redesign which resulted in the device being larger than initially expected. However, alternative approaches that can be explored in order to improve this were detailed in the design recommendations section of this thesis which may also improve the performance of the feedback delivered. The device was also designed to be non-intrusive and to use the *Oculus Touch* controllers which prevented any additional wearable devices needing to be worn, which is shown in literature to negatively impact presence. Results from the second study of this thesis suggested the air cannon successfully delivered satisfying feedback. Following this, participants indicated that they preferred the air feedback over vibrotactile feedback delivered by the *Oculus Touch* controllers. Furthermore, these results indicated that the air cannon condition had the most positive impact in terms



of presence over the standard vibrotactile feedback. Consequently, this satisfies the second (Can satisfying tactile feedback be created and delivered by a device that is non-intrusive and applicable for commercial virtual reality use?) and third (What is the impact on presence when using feedback delivered by a non-intrusive device?) research questions.

In addition to satisfying research questions of this thesis, the research also revealed some interesting results and findings that were not formally tested for. The first interesting finding which was present in both studies was that the results did not differ depending on the level of virtual reality experience that participants had. It could be expected that participants with more virtual reality experience would be more put off by a different haptic sensation or by the complete lack of haptic feedback. Participants with less experience could be more focused on the novelty of virtual reality rather than tactile feedback. However, results were similar the participants previous exposure to virtual reality. This could further support that haptic feedback has a large impact on presence.

A further interesting observation from the haptic device study involved the participants interaction with the game. In the experience, participants were presented with visible hands to deflect the balls with. It was observed that all participants only used the hands to deflect the balls and did not try to use any other part of their body. Furthermore, none of the participants commented when a ball would seemingly pass through where their body should be. This suggested that the participants were prepared to suspend some disbelief when playing such an experience.

A final interesting result seen from the haptic device study, which was not formally tested for, was the impact that a lack of feedback had on the participants ability to perform when compared with the vibration and air feedback conditions. This was confirmed by the logged game scores. In addition to this, participants also believed themselves to have performed worse and felt less motivated in the no feedback condition. This was supported by the presence questionnaire results, participant's body language and the custom questionnaire results. The reason for this could be due to the participant becoming uninterested in the game once tactile

feedback had been removed. Finally, while we cannot conclude that air haptics is an improvement over vibrotactile haptics as a larger sample of participants would be needed and aspects besides just presence would need to be investigated. We can conclude that from our results air haptics is on equal ground with vibrotactile haptics in certain game environments and is a promising alternative given more research in the area.

### **5.3 Limitations and Future Work**

This research has offered a different approach to haptic feedback which can be used with modern virtual reality technologies. However, due to the scope of the project and its aims some areas have not been explored. Whilst it was aimed for the device to be as universal as possible, the integration with existing virtual reality experiences, both games and visual experiences, was not considered.

An area that this research did not cover was how air feedback would perform for other types of haptic feedback when compared with controller vibrations. The work in this thesis focused on the replication of large, more obvious types of haptic feedback like forces and large shapes. However, an interesting area of research may be how air compares when used for different types of interactions. An example of this would be instead of indicating an opposing force it would signal the picking up of an object, a sensation that is suited well to vibrotactile feedback.

Following this, it was not queried how often participants play games, or on what platform. This could mean that if participants were avid console player they would be more accustomed to vibrational feedback. However, if participants are not interested in games or are primarily keyboard and mouse pc players then vibrotactile feedback would not be experienced as often. Consequently, players that are more used to experiencing vibrational feedback may feel more disturbed with the lack of feedback or on the other hand more sensitive to new types of feedback. It would be an interesting area to investigate whether these previous

experiences would have an effect on the participants reactions to different types of feedback.

A further area that was not considered during the creation of the device was multiple source directions. Currently the feedback is delivered from a single focus point meaning it is always felt from one direction. This would be an interesting research topic as the device could be modified to have higher degrees of freedom to better simulate multiple sources, a suggestion for this is briefly discussed in the device limitations and improvements section of chapter four. These device improvements may also lead to compelling future research opportunities.

A final limitation of the study used to verify the device was that a usability questionnaire was not used. This could have provided an insight into how participants felt towards the device set up and general use. This is a consideration for future work in this area.

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# Appendices

# Appendix A

Participant Number: .....

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## Experience Questionnaire

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Please characterize your experience in the environment, by circling the appropriate number of the 7 point scale, in accordance with the question.

### General Questions:

Age: \_\_\_\_\_ Which Gender do you identify with? \_\_\_\_\_

**How experienced would you say you are with virtual reality technology?**

(NOT AT ALL) (VERY EXPERIENCED)  
1 2 3 4 5 6 7

### Experience Questions:

**1. How much were you able to control events?**

(NOT AT ALL) (COMPLETELY)  
1 2 3 4 5 6 7

**2. How responsive was the environment to actions that you initiated (or performed)?**

(NOT AT ALL) (COMPLETELY)  
1 2 3 4 5 6 7

**3. How natural did your interactions with the environment seem?**

(EXTREMELY ARTIFICIAL) (COMPLETELY NATURAL)  
1 2 3 4 5 6 7

**4. How much did the visual aspects of the environment involve you?**

(NOT AT ALL) (COMPLETELY)  
1 2 3 4 5 6 7

**5. How natural was the mechanism which controlled movement through the environment?**

(EXTREMELY ARTIFICIAL) (COMPLETELY NATURAL)  
1 2 3 4 5 6 7

**6. How compelling was your sense of objects moving through space?**

(NOT AT ALL) (VERY COMPELLING)  
1 2 3 4 5 6 7

**7. How much did your experiences in the virtual environment seem consistent with your real world experiences?**

(NOT CONSISTANT) (VERY CONSISTANT)  
1 2 3 4 5 6 7

**8. Were you able to anticipate what would happen next in response to the actions that you performed?**

(NOT AT ALL) (COMPLETELY)  
1 2 3 4 5 6 7

**9. How completely were you able to actively survey or search the environment using vision?**

(NOT AT ALL) (COMPLETELY)  
1 2 3 4 5 6 7

Participant Number: .....

**10. How compelling was your sense of moving around inside the virtual environment?**

(NOT COMPELLING) (VERY COMPELLING)  
1 2 3 4 5 6 7

**11. How closely were you able to examine objects?**

(NOT AT ALL) (VERY CLOSELY)  
1 2 3 4 5 6 7

**12. How well could you examine objects from multiple viewpoints?**

(NOT AT ALL) (EXTENSIVELY)  
1 2 3 4 5 6 7

**13. How involved were you in the virtual experience?**

(NOT INVOLVED) (COMPLETELY ENGROSSED)  
1 2 3 4 5 6 7

**14. How much delay did you experience between your actions and expected outcomes?**

(NO DELAYS) (LONG DELAYS)  
1 2 3 4 5 6 7

**15. How quickly did you adjust to the virtual experience?**

(NOT AT ALL) (LESS THAN ONE MINIUTE)  
1 2 3 4 5 6 7

**16. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?**

(NOT AT ALL) (VERY PROFICIENT)  
1 2 3 4 5 6 7

**17. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?**

(NOT AT ALL) (PREVENTED TASK PERFORMANCE)  
1 2 3 4 5 6 7

**18. How much did the control devices interfere with the performance of assigned tasks or with other activities?**

(NOT AT ALL) (INTERFERED GREATLY)  
1 2 3 4 5 6 7

**19. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?**

(NOT AT ALL) (COMPLETELY)  
1 2 3 4 5 6 7

**20. How well could you actively survey or search the virtual environment using touch?**

(NOT AT ALL) (COMPLETELY)  
1 2 3 4 5 6 7

**21. How well could you move or manipulate objects in the virtual environment?**

(NOT AT ALL) (COMPLETELY)  
1 2 3 4 5 6 7

**22. How completely were your senses engaged?**

(NOT AT ALL) (COMPLETELY)  
1 2 3 4 5 6 7

**23. Additional Comments:**

# Appendix B

Participant Number: .....

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## Comparison Questionnaire

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For each question please circle the answer that best represents your preference with respect to all three of the experiences:

**1. I enjoyed playing the game more...**

(1) With Vibration      (2) With Air      (3) Without Air or Vibration      (4) No Preference

**2. I found it more comfortable to play...**

(1) With Vibration      (2) With Air      (3) Without Air or Vibration      (4) No Preference

**3. I felt more immersed in the game...**

(1) With Vibration      (2) With Air      (3) Without Air or Vibration      (4) No Preference

**4. I felt uneasy...**

(1) With Vibration      (2) With Air      (3) Without Air or Vibration      (4) No Preference

**5. I felt more skilful...**

(1) With Vibration      (2) With Air      (3) Without Air or Vibration      (4) No Preference

**6. I felt more frustrated playing...**

(1) With Vibration      (2) With Air      (3) Without Air or Vibration      (4) No Preference

**7. I felt more engaged...**

(1) With Vibration      (2) With Air      (3) Without Air or Vibration      (4) No Preference

**8. I had to concentrate the most playing...**

(1) With Vibration      (2) With Air      (3) Without Air or Vibration      (4) No Preference

**9. I felt more challenged while playing...**

(1) With Vibration      (2) With Air      (3) Without Air or Vibration      (4) No Preference