

**Using binaural audio for inducing
intersensory illusions to create
illusory tactile feedback in virtual reality**

By De Villiers (ID) Bosman

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Faculty of Engineering, Built Environment and Information Technology

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Supervisor: Koos de Beer

Co-supervisor: TJD Bothma

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Declaration

I declare that the Master's dissertation, which I hereby submit for the degree MIS (Multimedia) at the University of Pretoria, is my own work and has not been previously submitted by me for a degree at another university.

Isak De Villiers Bosman

Date

Abstract

Virtual reality has the potential to simulate a variety of real-world scenarios for training- and entertainment-purposes, as it has the ability to induce a sense of “presence”: the illusion that the user is physically transported to another location and is really “there”. VR and VR-technologies have seen a recent market resurgence due to the arrival of affordable, mass-market VR-display systems, such as the Oculus Rift, HTC Vive, PlayStation VR, Samsung GearVR, and Google Cardboard. However, the use of tactile feedback to convey information about the virtual environment is often lacking in VR applications.

This study addresses this lack by proposing the use of binaural audio in VR to induce illusory tactile feedback. This is done by examining the literature on intersensory illusions as well as the relationship between audio and tactile feedback to inform the design of a software prototype that is able to induce the desired feedback. This prototype is used to test the viability of such an approach to induce illusory tactile feedback and to investigate the nature of this feedback.

The software prototype is used to collect data from users regarding their experiences of this type of feedback and its underlying causes. Data collection is done through observation, questionnaires, interviews, and focus groups and the results indicate that the use of binaural audio in VR can be used to effectively induce an illusory sense of tactile feedback in the absence of real-world feedback.

This study contributes insights regarding the nature of illusory sensations in VR, focusing on touch-sensations. This study also provides consolidated definitions of immersion and presence as well as a consolidated list of aspects of immersion, both of which are used to detail the relationship between immersion, presence, and illusory tactile feedback. Findings provide insight into the relationship between the design of audio in VR and its ability to alter perception in the tactile modality. Findings also provide insight into aspects of VR, such as presence and believability, and their relationship to perception across various sensory modalities.

Keywords

Virtual reality, tactile feedback, audio feedback, illusory feedback, intersensory illusions, immersion and presence, audio-tactile mapping, usability testing

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1. Chapter 1 - Introduction

Virtual reality (VR) presents new ways of interacting with computer environments as if one is really “there” in the virtual environment. The recent development of affordable VR hardware, such as the Oculus Rift, HTC Vive, Samsung Gear VR, and Google Cardboard provides the opportunity for a significant increase of VR applications in a variety of situations (Cohen, Villegas & Barfield 2015). The effectiveness of VR lies in its potential to create a seamless environment in which one interacts with the computer world as with one’s natural environment (Seth, Vance & Oliver 2010).

This potential, however, relies on the VR technology’s ability to provide realistic feedback across the necessary modalities for interaction and immersion in the virtual environment (Cohen, Villegas & Barfield 2015). Research and development of VR tend to focus on the visual modality, leaving the audio and especially the haptic modality somewhat neglected (Meijden & Schijven 2009; Cohen, Villegas & Barfield 2015). This study focuses on what is known as “intersensory illusions”, which refer to using stimulation from one sensory modality to provide/alter perception of stimulation to another sensory modality (Biocca, Kim & Choi 2001; Bizley, Shinn-Cunningham & Lee 2012) to compensate for the lack of haptic feedback in modern VR applications.

1.1 Background to the study

Virtual reality (VR), also referred to as “synthetic environments” or “artificial reality” (Loftin & Kenney 1995) uses a computer interface to immerse a user in a 3-dimensional simulated environment that resembles reality (Miner & Stansfield 1994; Zyda 2005; Lucca 2009; Peterson & Robertson 2013; Lowood 2015) and is usually aimed at letting a user feel that they are “present” in the simulated reality (Loftin & Kenney 1995; Blake & Gurocak 2009; Lowood 2015). Virtual reality often uses specialized equipment such as head-mounted displays (HMDs) and data-gloves (Shaw et al. 1993; Miner & Stansfield 1994; Seth, Vance & Oliver 2010; Cohen, Villegas & Barfield 2015; Lowood 2015) and aims to create an experience that resembles a user’s natural environment by providing realistic feedback across multiple sensory modalities, such as visual, audio, and haptic (Shaw et al. 1993; Seth, Vance & Oliver 2010).

1.1.1 Virtual reality application

Virtual reality has been used for a number of applications, including space training (Loftin & Kenney 1995), vocational training (Fast, Gifford & Yancey 2004; Crison et al. 2005), and surgical training (Meijden & Schijven 2009; Jordan et al. 2014), telerehabilitation (Popescu et

al. 2000; Lucca 2009; Kairy et al. 2016), and has become an indispensable tool for training pilots (Satava 1993; Fast, Gifford & Yancey 2004; Peterson & Robertson 2013).

VR offers several advantages in learning, training, and treatment environments, such as the ability to collect objective information about a user's interaction and skill level in the training environment (Miner & Stansfield 1994; Peterson & Robertson 2013; Jordan et al. 2014), the ability to train even if the needed facilities (hardware, software, personnel, etc.) are not available or are too expensive (Miner & Stansfield 1994; Seth, Vance & Oliver 2010), a low-risk environment for potentially dangerous training exercises (Satava 1993; Peterson & Robertson 2013), control over objects/environments that might be difficult to control in real life (Carlin, Hoffman & Weghorst 1997; Morina et al. 2015), and allowing for users/operators to "experience" scenarios, such as emergencies, to better prepare them for those scenarios in real life (Miner & Stansfield 1994; Morina et al. 2015). An advantage of using VR for training (as opposed to non-VR computer-based applications) is that the user's instinctive knowledge about the real (physical) world is transferred to their knowledge of interactions of manipulations in the digital "world" (Shaw et al. 1993; Upshaw 1995; Seth, Vance & Oliver 2010).

1.1.2 Feedback in virtual reality

A factor that is often regarded as a determinant of the usefulness of VR as a tool for training is the realism/fidelity of the virtual environment (Satava 1993; Carlin, Hoffman & Weghorst 1997; Seth, Vance & Oliver 2010; Peterson & Robertson 2013). This involves providing accurate representations of the environment across multiple senses, including visual, audio, and haptic (Blake & Gurocak 2009). Haptic feedback can be divided into two categories: kinaesthetic and cutaneous. Kinaesthetic feedback refers to all force feedback that is sensed by the muscles and joints as they interact with an opposing force, while cutaneous feedback, also known as tactile feedback, refers to all sensations that are sensed through mechanoreceptors in the skin, such as texture, temperature, etc. (Brewster & Brown 2004). Kinaesthetic feedback is presented with force feedback devices, such as the PHANToM and the Rutgers-Master (Gomez, Burdea & Langrana 1995; Brewster & Brown 2004), while cutaneous feedback is presented with the use of tactile devices (Brewster & Brown 2004), such as vibrotactile devices (Cheng, Kazman & Robinson 1996; Hayden 2018) or electrotactile devices (Sato et al. 2007).

The use of haptic feedback in VR offers several advantages, such as an added level of realism (Popescu, Burdea & Bouzit 1999; Blake & Gurocak 2009), a more engaging experience (Lucca 2009), and an added channel of feedback which can be useful in the absence of reliable visual feedback (Popescu, Burdea & Bouzit 1999). The use of haptic feedback is especially useful

when performing telemanipulation, in which an operator remotely controls and interacts with an environment (Niemeyer & Slotine 2004), often with the use of dextrous devices (Turner et al. 1998; Koyama et al. 2002).

While video and audio are commonplace in a computing environment, devices that provide haptic feedback to the user are often lacking in VR (Cheng, Kazman & Robinson 1996), because they tend to be quite large and expensive (Cheng, Kazman & Robinson 1996; Berkley, Kim & Hong 2012). Karam, Russo and Fels (2009) point out that the human cutaneous system as an input channel can potentially be used to convey a lot of information to the user and is a mostly-untapped input channel in modern computing systems (Karam, Russo & Fels 2009). This is supported by van Mensvoort (2002) who points out that computers “engage only a fraction of the human sensory bandwidth” and suggests that haptic-feedback can enrich computer interfaces by making computing interfaces more natural and turning one-way touch-interaction into a two-way interaction with touch feedback from the computer (van Mensvoort 2002).

Advantages of using audio as a feedback mechanism in a computing environment include providing additional feedback without using up/cluttering precious screen real-estate (Gaver 1989; Brewster, Wright & Edwards 1993; Shaw et al. 1993), the ability to represent information that is not easily visually representable (Monk 1986), the ability to complement visual information, adding redundancy to information representation which may help users with recall, the ability to represent sound in 360° around a user as opposed to the visual channel’s limited field of vision, effectively capturing users’ attention (Brewster, Wright & Edwards 1993), and finally allowing visually impaired users to use the interface (Brewster, Wright & Edwards 1993; Iglesias et al. 2004). Some disadvantages of audio feedback mechanisms are its limited use in a loud environment (Brewster & Brown 2004), the ability to disturb/annoy other people (Brewster & Brown 2004), and the fact that blind people prefer not to wear earphones, which are often much needed for effective audio feedback, outside (Brewster & Brown 2004).

Binaural/three-dimensional audio exploits the ability of our ears to localize sound using a number of cues, including head-related transfer functions (HRTFs) which are a result of sound interacting with the head, torso, shoulders and ears (Brown & Duda 1998; Wanrooij & Opstal 2007) as well as the differences between audio that is heard in each ear, i.e. binaural differences (Wanrooij & Opstal 2007).

1.1.3 Intersensory illusions

One possible solution to make up for the lack of haptic feedback in VR is the use of intersensory illusions. Intersensory illusions refer to illusions where stimulation from one modality influences/creates perceived stimulation in another (possibly unstimulated) modality (Biocca, Kim & Choi 2001; Bizley, Shinn-Cunningham & Lee 2012). There are different kinds of intersensory illusions, such as intersensory bias/intermodal influence (Biocca, Kim & Choi 2001; Heineken & Schulte 2007) and cross-modal transfers (Biocca, Kim & Choi 2001; Biocca et al. 2002).

Intersensory bias occurs when two or more channels present conflicting information and a user experiences a bias toward one of the channels (Biocca, Kim & Choi 2001; Bizley, Shinn-Cunningham & Lee 2012; Pérez-Bellido et al. 2015). This phenomenon is often attributed to what is known as the “simultaneity constancy”: the brain’s tendency to integrate input from different modalities to such an extent that when there is a discrepancy between modalities, the brain sometimes alters the perception of one or more modality to keep this integration intact (Jousmäki & Hari 1998; Lecuyer et al. 2000; Biocca, Kim & Choi 2001; Harrar & Harris 2008; Pérez-Bellido et al. 2015). Perhaps the most pervasive and stable example of this phenomenon in the literature is the so-called “size-weight illusion” where, presented with two objects of equal weight but different sizes, an observer will perceive the smaller object as being heavier (Charpentier 1891; Murray et al. 1999; Heineken & Schulte 2007).

Cross-modal transfer occurs when stimulation in one sensory channel leads to perceived stimulation in another unstimulated channel (Biocca, Kim & Choi 2001; Biocca et al. 2002) similar to the experience known as synaesthesia where stimulation in one channel produces involuntary stimulation of an atypical nature in another sensory channel (Baron-Cohen et al. 1996; Brang, Williams & Ramachandran 2012). An example of this in the field of VR is that of Biocca, Kim and Choi (2001) and Biocca et al. (2002) that let users interact with a virtual spring in a VR environment, where users reported a force-feedback even though there was no force-feedback present (Biocca, Kim & Choi 2001; Biocca et al. 2002). The aforementioned study used visual and audio feedback to create the illusion of tactile feedback in the virtual environment. In both of these illusions, it is usually the visual stimulation that skews the perception of stimulation in other channels, a phenomenon known as “visual capture” (Welch & Warren 1980; Biocca et al. 2002).

Although visual feedback usually skews the feedback from other modalities, there are examples of audio feedback skewing the perceived visual feedback, perhaps the most well-known being the double flash illusion (DFI) where a single flash of light is perceived as two

distinct flashes if it is accompanied by two auditory beeps (Shipley 1964; Shams, Kamitani & Shimojo 2000; Shams, Kamitani & Shimojo 2002; Bizley, Shinn-Cunningham & Lee 2012; Pérez-Bellido et al. 2015). This illusion as well as others, such as the parchment-skin illusion (Jousmäki & Hari 1998), shows that audio can be utilized to dominate the other senses and create intersensory illusions that skew the perceived feedback towards that of the audio feedback. Most of the literature, however, focuses on the interplay between audio and visual feedback, specifically “visual capture” (Welch & Warren 1980; Biocca, Kim & Choi 2001; Lecuyer et al. 2001; Biocca et al. 2002; Mishra et al. 2007; Hecht & Reiner 2008), while only a small amount of the literature focuses on audio-haptic illusion (Jousmäki & Hari 1998; Giordano et al. 2012).

Audio and tactile feedback share certain abstract qualities that allow them to be mapped cross-modally, such as spatial location, intensity, frequency/rate, and roughness/texture (Hoggan & Brewster 2006a; Hoggan & Brewster 2006b; Hoggan & Brewster 2007). In a virtual environment, one can provide audio seemingly originating from a 3D-spatialized source using binaural audio (Seligmann, Mercuri & Edmark 1995), which provides more realistic audio renderings than those used in traditional intersensory experiments such as the double flash illusion (Shipley 1964; Pérez-Bellido et al. 2015).

1.2 Problem statement

The overview above leads to the following problem statement:

- Haptic feedback, specifically tactile/cutaneous, presents significant potential advantages in the application areas where VR is or may be used.
- This type of feedback, however, is often lacking in VR technology due to its high cost and complexity.
- While intersensory illusions have been successfully used to provide stimulation across various senses, in both real-world and VR contexts, the use of these illusions does not extend to the induction of illusory tactile feedback in a VR context.

1.3 Statement of purpose

Due to the lack of focus on VR technologies that aim to induce tactile feedback, this study focuses on the use of intersensory illusions to induce these types of stimuli. The purpose of this study is to develop a VR application that makes use of visual- and audio-feedback to induce an illusory tactile sensation. The study focuses on the determinants of illusory sensations as well as the relationship between the audio and tactile modality and applies this

in the creation and testing of a VR application that can successfully create the illusion of tactile stimulation in the total absence of any real-world tactile stimuli.

1.4 Significance of this study

The addition of tactile feedback presents many advantages in the context of VR applications (as discussed in sections 2.3.1.3 and 2.4.2.1), but is often neglected in favour of other modalities, specifically the visual modality. By exploiting determinants of intersensory illusions as well as the relationship between the audio and tactile modalities, this study provides insight into the realm of sensory perception in VR as well as the cause of intersensory illusions. These insights provide context for the creation of other VR applications that aim to supplement the lack of sensory feedback in one modality with the use of other modalities.

1.5 Research questions

The goal of this study was achieved by answering the following research questions. Additionally, sub-questions were derived from the primary research question and were answered using a variety of sources, as shown in Table 1 below.

1.5.1 Primary research question

How can the illusion of tactile feedback be created using binaural audio in virtual reality to induce intersensory illusions?

1.5.2 Sub-questions

Table 1: the sub-questions derived from the primary research question and the sources which are used to answer each

Question	Description	Source
Which characteristics of both audio and haptic feedback can be utilized to design an effective intersensory illusion between them?	These characteristics inform the design of the application which serves as an implementation of a strategy that aims to induce illusory tactile sensations.	Literature and empirical

Which underlying causes of intersensory illusions can be utilised to induce illusory tactile sensations?	This requires an investigation of the literature to inform the design of the implementation.	Literature and empirical
What is the role of immersion and presence in the creation of illusory tactile feedback?	Investigation into these integral concepts inform the design of the prototype and can also be used to contextualise the results of the study.	Literature and empirical
How can the effectiveness of the intersensory illusion be tested?	Preliminarily answering this question informs the design of the study itself. Evaluating the effectiveness of the implementation provides necessary evidence to answer the main research question.	Literature and empirical

1.6 Research design

This study's focus on the experiential aspects of human perception pointed towards an interpretivist paradigm and thus a qualitative methodology (Pickard 2013:1). In order to study the experiences caused by the implementation in the attempt to achieve its goal, a usability test was chosen as the research method, as it involves exposing one/more participant(s) to a software implementation and gathering data regarding its use (Barnum 2010:1).

During and after the test, data were collected using four methods, observations, questionnaires, qualitative interviews, and focus groups, each of which made a unique contribution in terms of research data (as is discussed in section 3.4.5). The qualitative focus during data collection was met with qualitative data analysis, specifically constant comparative analysis. During this process, core concepts in the research data were identified and used to draw inferences (Pickard 2013:23) which informed the main findings of the study.

1.7 Limitations

The current section discusses the limits within which the study was carried out.

1.7.1 Generalisability

As qualitative research does not aim to produce generalizable results, there is no guarantee that the results of this study can be applied to a wider context of environments and populations (Pickard 2013:1). In this study, this limitation is largely the result of the process of usability testing and data collection, which focused on gathering rich, descriptive data from a relatively small number of individuals. As the research is done within a specific context and group of people, the findings are thus not generalizable to the broader population.

1.7.2 Demographic factors

Since the study relied on participants for data collection, a number of demographic factors came into play, such as age, gender, ethnicity, etc. All of these factors have the potential to influence the results in various ways. However, the focus of the current study was not to investigate the role of these factors and as such they were not used as part of the study's research design.

1.7.3 Technological aspects

The technologies used for the implementation of the software system to induce illusory tactile sensations were largely chosen based on availability. The University of Pretoria's Virtual Reality and Interaction (VRI) lab provided access to certain VR equipment, which placed limits regarding how technological implementation could be carried out. The outcomes of the usability tests with the available technologies are thus not generalizable to the use of any VR equipment.

1.7.4 Limits of implementation

As discussed in section 4.2.2.4.2, a deliberate choice was made during implementation to limit the use of certain parameters which are shared by the audio and tactile modalities, since the focus of this study was not to provide a broad experimentally-tested range of these parameters. As such, only some of these parameters were selected to be varied for the purposes of the software implementation. However, it is possible that the use of different parameters would induce different sensations for participants when they are modified.

1.8 Outline of chapters

The current chapter provided an overview of the problem to be addressed and the means of addressing it, including the use of existing literature to answer sub-questions within the research and the use of empirical data which stem from the main research method: a usability test. Chapter 2 continues by establishing the context for the current research and answering some of the sub-questions using existing literature. Chapter 3 establishes the means of carrying out the study by describing the research methodology, software process model, research method, data collection methods, and data analysis method used for the current study. Chapter 4 describes in detail the hardware and software concerns for the implementation of a system to induce illusory tactile sensations and also describes all the design choices guiding the implementation of this system. Chapter 5 discusses research data, starting with data resulting from a pilot study and how these informed changes in the design of the final implementation of both the system implementation and the research design. The results of the main research method are then discussed, making use of data gathered across all means of data collection. Chapter 6 answers each research question and suggests topics for further research.

2. Chapter 2 - Literature review

This chapter first discusses the concept of virtual reality, its origin, and development as well as related concepts, then applications of virtual reality in the real world as well as its advantages and disadvantages. This is followed by a detailed discussion of the terms “immersion” and “presence”, including the factors that influence them and their causes in VR. This chapter then discusses feedback modalities in VR, specifically audio and haptic, including their advantages and disadvantages as well as the use of multimodal feedback and the effects thereof. The chapter then concludes by discussing intersensory illusions, some notable examples, different types of illusions, their causes, why they are useful, and finally a discussion of the mapping between audio and tactile.

2.1 *Virtual reality*

Virtual reality (VR), also referred to as “synthetic environments” or “artificial reality” (Loftin & Kenney 1995) uses a computer interface to immerse a user in a 3-dimensional virtual environment (VE) that resembles reality (Miner & Stansfield 1994; Zyda 2005; Lucca 2009; Peterson & Robertson 2013; Lowood 2015). It is usually aimed at letting a user feel that they are “present” in the simulated reality (Loftin & Kenney 1995; Blake & Gurocak 2009; Lowood 2015). VR requires specialised equipment such as head-mounted displays (HMDs) which deliver stereoscopic displays and real-time head tracking (Earnshaw, Gigante & Jones 1993:2; Lowood 2015). VR often also uses specialised input devices, such as motion controllers (Shaw et al. 1993; Seth, Vance & Oliver 2010) or gesture controllers (Seth, Vance & Oliver 2010; Coelho & Verbeek 2014). Both of these use various technologies to track a user’s hand movements to provide input to the system (Seth, Vance & Oliver 2010; Coelho & Verbeek 2014). VR aims to create an experience that resembles a user’s natural environment by providing realistic feedback across multiple sensory modalities, such as the visual, audio, and haptic modality (Shaw et al. 1993; Seth, Vance & Oliver 2010).

Bearing in mind the discussions put forth by the research above in the field, this study puts forth and uses the following consolidated definition of virtual reality: *A computer-simulated reality that uses non-traditional input and output devices to provide feedback across multiple sensory modalities. VR immerses users in a simulated environment that resembles their reality to some extent and ideally allows them to interact with this reality as they would with their natural environment. Since VR allows users to believe that they are “really there” in a VE, the definition of VR refers to the user’s experience rather than the underlying technology that facilitates this experience and is tightly linked with the concept of “presence” (Steuer 1992), which is discussed in section 2.3.2.*

2.1.1 VR display devices

VR systems often use HMDs to display a VE to a user (Earnshaw, Gigante & Jones 1993). An HMD is a device that is worn on a viewer's head and provides stereoscopic displays while blocking out their visual input from the real world and also tracks the viewer's head movement and adjusts the perspective of the viewer in the VE accordingly (Earnshaw, Gigante & Jones 1993; Southard 1995). The use of an HMD creates the illusion that the user is immersed "inside" the VE, as it models the visual input the viewer would normally experience in their everyday interaction with the real world (Southard 1995). Some variations of HMDs exist, for example:

- optical see-through HMDs, which place a semi-transparent screen in front of the user's eyes, allowing them to see both the real world and superimposed digital representations simultaneously (Azuma 1997; Tamura, Yamamoto & Katayama 2001)
- video see-through HMDs, which work similar to traditional HMDs, but also contain video cameras mounted on the top of the device (Azuma 1997; Tamura, Yamamoto & Katayama 2001). The feed from the video cameras can be digitally modified or augmented and then displayed to the user (Azuma 1997; Mann 1999).

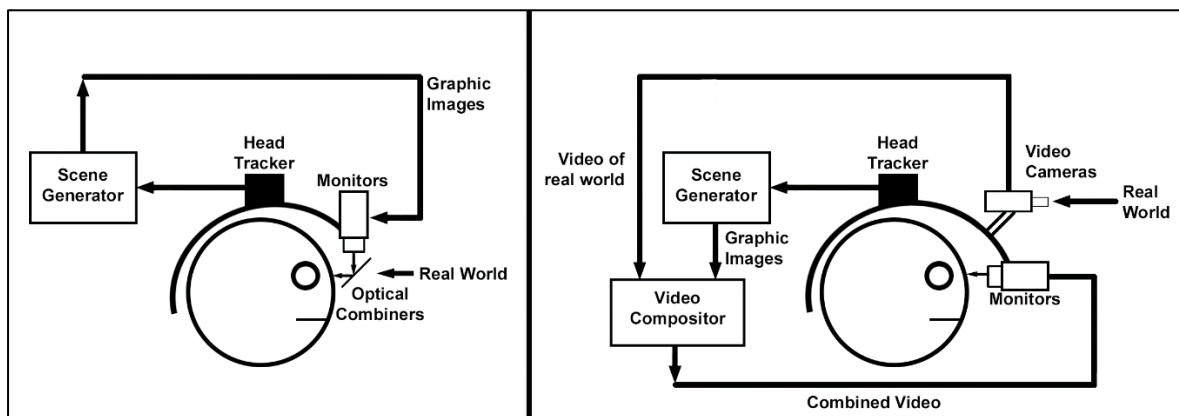


Figure 1: Conceptual diagrams for an optical see-through HMD (left) and a video see-through HMD (right) (Azuma 1997:7, 9)

The applications for these HMD variants are discussed in section 2.1.3.

Apart from HMDs, VR systems can also make use of several types of displays, including screens/monitors (Gomez, Burdea & Langrana 1995; Southard 1995), CAVEs (Southard 1995; Springer & Gadh 1996) and responsive workbenches (Krueger & Froehlich 1994; Brooks 1999). A VR system using a screen/monitor displays a VE using 3D graphics and allows the user to interact with this environment, with optional head-tracking and other input devices (Gomez, Burdea & Langrana 1995; Southard 1995). A cave automatic virtual environment

(CAVE) refers to a physical structure that a user can enter which then encloses them and displays images on the walls surrounding them, thus creating an illusory environment around the user (Southard 1995; Springer & Gadh 1996). A responsive workbench is a device that resembles a real workbench, but instead of holding physical objects and tools, it displays virtual versions and allows a user to interact with and modify them (Krueger & Froehlich 1994). For example, one could perform virtual “surgery” on a responsive workbench with the use of hand-tracking devices, such as the *Dataglove* (Krueger & Froehlich 1994). It should be noted that the devices above are by no means an exhaustive list.

These devices and systems meet some or even most of the requirements for a VR system and might offer unique advantages, such as a CAVE allowing for a group of people to interact in the same physical space (Springer & Gadh 1996). However, this study focuses on VR systems that use HMDs, for the following reasons:

- Unlike conventional displays, HMDs have the ability to completely “immerse” the viewer by removing them from their everyday reality by blocking out stimuli from their surrounding environment. As such, they provide only sensory stimuli about the VE (Brooks 1999; Heineken & Schulte 2007). Biocca (1999) refers to this concept as “sensory saturation.” This concept is discussed along with that of immersion in more detail in section 2.3.1.
- Modern HMDs are also relatively affordable (Kerr 2016a) compared to more complex systems, such as CAVEs, as discussed in section 2.1.2.2.

2.1.2 History of VR

This section discusses the origins of virtual reality concepts and technologies as well as its recent resurgence into the consumer market.

2.1.2.1 *The origins of VR*

There is no singular event or invention that signalled the start of what we know today as VR, but rather a series of ideas and inventions that gave rise to the enabling technologies for modern-day VR implementations. This includes a vast amount of work, from the writings of science-fiction authors, such as Arthur C. Clarke and William Gibson, that imagined the existence of technologies resembling modern-day VR, to the postulation and implementation of hardware and software systems that realise these ideas (Earnshaw, Gigante & Jones 1993:1).

The first known implementation of a system that bore a resemblance to the concept of VR as we know today was the *Sensorama*, invented by Morton Heilig in 1962 (Earnshaw, Gigante & Jones 1993:1). The *Sensorama* was a system that attempted to immerse a viewer in a different

reality by providing multisensorial input, such as visual, aural, haptic, and olfactory (Earnshaw, Gigante & Jones 1993:1). The system, however, was not interactive (Earnshaw, Gigante & Jones 1993:1). Three years later, computer graphics pioneer Ivan Sutherland proposed the idea for a display that changes its presentation depending on where the viewer looks (Sutherland 1965). He proposed that this technology could be used to create the “ultimate display”, in which computer-generated stimuli are perceived as being as real as the viewer’s everyday world (Sutherland 1965). He was also involved in creating the first head-mounted display, which used two separate cathode ray tube (CRT) displays to display separate visual information for each eye, also known as a stereoscopic display (Sutherland 1968). This device also used a mechanical arm that hung from the ceiling to track the user’s head movement and modified what is displayed based on the user’s head movement, thus creating a digital 3-dimensional representation that the user perceived in the same way that they perceive in the real world (Sutherland 1968).

Some of the first implementations of VR for practical use were flights simulators, developed by the US Air Force’s Armstrong Medical Research Laboratories, and astronaut training systems, developed by NASA (Earnshaw, Gigante & Jones 1993:1; Satava 1993; Loftin & Kenney 1995). Both of these made major contributions to developing the technologies that are now commonplace in VR systems (Earnshaw, Gigante & Jones 1993:1; Satava 1993; Loftin & Kenney 1995).

The advent of technologies for creating and presenting virtual worlds has also given rise to related concepts and technologies, such as augmented reality (AR) (Milgram & Kishino 1994). One of the first AR systems was developed to aid in aircraft manufacturing by augmenting the viewer’s field of view with information relevant to their current task by using see-through HMDs, stereoscopic displays, and head-tracking (Caudell & Mizell 1992). The technological possibility of creating varying degrees of simulated/modelled reality has also led to the concept of a continuum between pure reality and purely simulated reality, known as mixed reality (Milgram & Kishino 1994), which is discussed in section 2.1.3.

2.1.2.2 The resurgence of VR

The 1990s saw a surge of research and development in the field of VR with a great deal of expectation for its future (Bowman & McMahan 2007; Campbell 2012) with many believing that it would soon be a natural part of everyday life (Earnshaw, Gigante & Jones 1993). Although many of these applications and endeavours were successful in achieving their goals (Earnshaw, Gigante & Jones 1993; Loftin & Kenney 1995; Brooks 1999), the use of VR was still in a “niche state” at the end of the millennium (Springer & Gadh 1996; McGill et al. 2015). Two reasons for this were its high cost (Springer & Gadh 1996; McGill et al. 2015) and

technological limitations, such as low screen resolution and system latency (Brooks 1999). Thus, during this time, VR saw very limited use in specific practical applications, such as medicine, flight- and military-training, and industrial use such as engineering and product development (Satava 1993; Astheimer & Rosenblum 1999; Brooks 1999; Campbell 2012).

Astheimer and Rosenblum (1999) postulated that a shift in focus from pure industry-use to VR applications for mass-market consumers, such as for home and office use, would change VR's application from its niche state to mainstream use (Astheimer & Rosenblum 1999). The gaming industry saw this shift in 2012 when the Oculus Rift headset was announced (Campbell 2012; Xiao & Benko 2016). The Oculus Rift, currently owned by Facebook, is a consumer HMD that works with desktop computers (Desai et al. 2014; Cohen, Villegas & Barfield 2015) and costs 399USD, as of February 2018 (Oculus 2018). Since its announcement, other technology companies have followed suit and announced their own consumer VR products, such as:

- Valve's HTC Vive (<https://www.vive.com/us/product/vive-virtual-reality-system/>)
- Samsung's Gear VR (<http://www.samsung.com/global/galaxy/wearables/gear-vr/>)
- Sony's PlayStation VR (<https://www.playstation.com/en-gb/explore/playstation-vr/>)
- Google's Cardboard (<https://vr.google.com/cardboard/>).

These were created with the aim of creating a mass-market for VR applications (Cohen, Villegas & Barfield 2015; Kerr 2016b). With the advent of these new consumer VR products, VR is predicted to become a multi-billion dollar industry with a user base consisting of millions of users in the next ten years (Perry 2016; Lee & Stewart 2016; Reuters 2017; Business Insider 2017).

As mentioned, VR-related technologies have given rise to a range of concepts and technologies that aim to mix the user's everyday reality with varying degrees or methods of virtual reality and vice versa.

These can be broadly categorised as follows (Mann 2002; Schnabel et al. 2007):

- mixed reality
- augmented reality
- augmented virtuality
- mediated reality
- mediated virtuality
- amplified reality
- virtualized reality.

As the following section indicates, the distinction and relationship between these categories are not always clear (Milgram & Colquhoun 1999; Schnabel et al. 2007). Nonetheless, the following section discusses each of these categories in turn.

2.1.3 Mixed reality

Using immersive technologies, such as HMDs, and input mechanisms, such as motion controllers and gesture controllers (Seth, Vance & Oliver 2010), it is possible to achieve varying degrees of reality/virtuality with regards to sensory input and output (Milgram & Kishino 1994; Milgram et al. 1995). This continuum of real/virtual is called mixed reality (MR), which refers to the merging of the real world with a virtual world to varying degrees and vice versa (Milgram & Kishino 1994; Milgram et al. 1995; Tamura, Yamamoto & Katayama 2001). This continuum is illustrated in Figure 2. It should be noted that the figure does not contain all of the aforementioned categories, as it is meant to be used as a baseline for defining mixed reality.

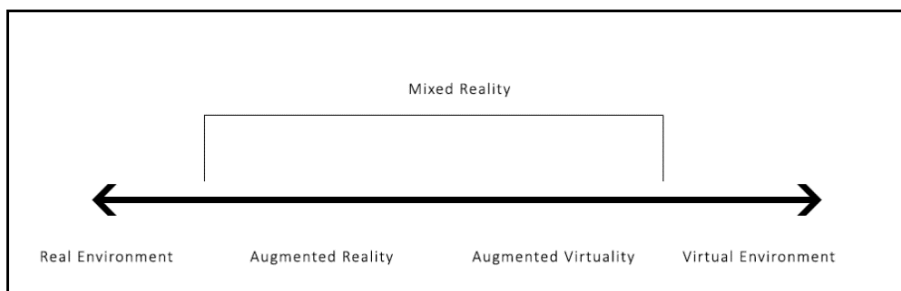


Figure 2: Simplified representation of a "virtuality continuum" (Milgram & Kishino 1994:3)

As can be seen, mixed reality exists between two extremes on a continuum: the real environment and the virtual environment. The real environment, for the purposes of this study, consists of everything that has an objective existence in our world and can be perceived without the mediation of display technologies (Milgram & Kishino 1994; Lombard & Ditton 1997). On the other hand, the virtual environment consists of anything that is visualised/synthesised using a computer or other electronic device, but does not form part of the real environment (Milgram & Kishino 1994; Milgram et al. 1995). From a more philosophical perspective, one can consider the real environment (reality) to be able to sustain itself without relying on some form of external processing, while VR's existence relies on an external information processor to exist (Whitworth 2007), in other words, the reality and environment only exist in the form of software (Sheridan 2000). Two related concepts, augmented reality and augmented virtuality exist between these two extremes on the continuum above (Milgram & Kishino 1994; Milgram et al. 1995).

2.1.3.1 *Augmented reality*

Augmented reality (AR) refers to augmenting the real-world's 3D-environment with 3D virtual objects, ideally creating the illusion that these objects reside in the same 3D-space (Azuma 1997; Schraffenberger & Van der Heide 2013). AR-systems typically use specific technologies, such as:

- **HMDs:** specifically, HMDs that allow the user to see both the real world and the overlaid virtual objects. These can be both optical see-through HMDs, similar to heads-up displays (HUDs) that are used by military aircraft, as well as video see-through HMDs that record the real-world as the user would see it and overlay this video input with virtual objects (Milgram et al. 1995; Azuma 1997; Tamura, Yamamoto & Katayama 2001).
- **Wearable devices:** electronic devices that are small and lightweight enough to be worn by the user without causing discomfort that capture input from both the user and the environment. These devices often provide location-aware as well as context-aware services that track the user's position, actions, and activities in real time and provide the user with timely information or functionality based on this data (Barfield 2015:1).
- **Hand-held computers:** by using the built-in technologies, such as the GPS or video camera, of hand-held computers, such as smartphones, a device can overlay the camera feed from such a device with virtual objects using location-based services (Barfield 2015; Kim & Hyun 2016).

Besides visual augmentation, AR can also refer to augmenting the user's audio perception, for example by adding specific audio cues based on a user's location (Bederson 1995). It can also alter the user's sense of touch (generally referred to as haptic perception, which is discussed in section 2.4.2), for example by altering the stiffness perception of a real-world object based on interaction with virtual objects (Jeon & Choi 2009).

Although AR is mediated by technologies such as those discussed above, Azuma (1997) points out that the concept of AR is not bound to specific technologies and rather refers to any system that adheres to the following criteria (Azuma 1997):

- The system combines the real world with a virtual world.
- The system does this interactively in real time.
- The system does this in three dimensions.



Figure 3: The Microsoft HoloLens (left) is a commercially available optical see-through HMD (Microsoft 2016). The Samsung GearVR (right) uses a smartphone's built-in camera, giving it video see-through capabilities (Samsung 2016)

Therefore, AR is distinct from VR regarding where each “takes place” and what information is provided or withheld by each (Azuma 1997). VR isolates the user from the real world and immerses them in a virtual world whereas AR takes place in the real world and augments the real world with virtual objects that are perceived as being part of the real world (Azuma 1997; Barfield 2015). In other words, AR supplements the viewer’s reality while VR becomes the user’s reality (Azuma 1997; Barfield 2015).

2.1.3.2 Amplified reality

Closely related and yet complementary to AR, amplified reality refers to publicly enhancing the perceivable aspects of an object by using embedded computational technology (Falk, Redström & Björk 1999). Although subtle, the difference between AR and amplified reality is significant, as the flow of information about the object in an amplified reality system is controlled by the object itself whereas it is controlled by the viewer in an AR system. This is done through the use of embedded computational resources which control the properties and representation of an object, similar to the concept of ubiquitous computing (Falk, Redström & Björk 1999; Schnabel et al. 2007).

When an object’s properties and representation are changed with the use of this technology, i.e. when the object is “amplified”, the object itself is said to be modified, since users of amplified reality technology will perceive the object differently (Falk, Redström & Björk 1999; Schnabel et al. 2007). Because an object controls its representation and properties, amplified objects are perceived similarly by all users of amplified reality, thus placing emphasis on shared experiences (Falk, Redström & Björk 1999; Schnabel et al. 2007). An example of an amplified reality device is a wearable device called the *Hummingbird*, which indicates the presence of other people with *Hummingbird* devices in the area by using visual and aural

feedback, thus amplifying the user's presence in the environment (Falk, Redström & Björk 1999; Holmquist, Falk & Wigström 1999).



Figure 4: A person wearing a Hummingbird device (Holmquist, Falk & Wigström 1999:7)

2.1.3.3 Augmented virtuality

On the other end of the spectrum as AR, augmented virtuality (AV) refers to augmenting fundamentally virtual environments with real-world objects by adding video or texture data from the real world into the virtual world (Milgram & Kishino 1994; Milgram et al. 1995; Wang & Dunston 2011). This differs from AR in the sense that the user is immersed in and can thus interact with and modify a virtual world that contains instances of “unmodelled” objects as viewed directly in the real world (Milgram et al. 1995; Milgram & Colquhoun 1999; Wang & Dunston 2011). AR, on the other hand, lets users be in and interact with and modify the real world that contains instances of modelled objects from a virtual world (Milgram et al. 1995; Milgram & Colquhoun 1999; Wang & Dunston 2011).

Two approaches for adding reality to virtuality are:

- by adding either directly viewed objects, such as using chroma-keying (“green screening”) to let users view their body/limbs instead of a modelled version of them (Drascic & Milgram 1996; McGill et al. 2015)
- by adding stereoscopic video footage to a simulation (Drascic & Milgram 1996; Drascic & Milgram 1997; McGill et al. 2015).

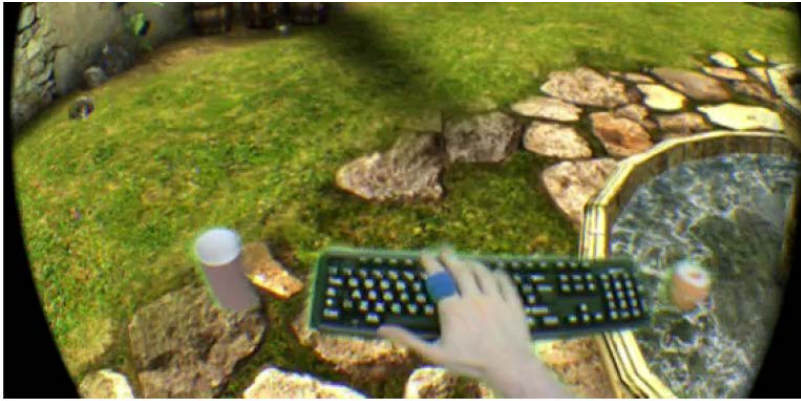


Figure 5: Chroma-keying is used to show the user's hands and keyboard in real time without disrupting the user's experience (McGill et al. 2015:7)

A fundamental difference between VR and AV is that, while a VR simulation might have virtual objects that correspond to real-world objects, such as a virtual hand that is controlled by a user (Popescu, Burdea & Bouzit 1999), the objects are still modelled in the virtual world (Milgram et al. 1995). Thus, these objects do not reside in the real world, while AV superimposes unmodelled objects, such as video or textures, from the real world into the virtual world (Milgram et al. 1995).

2.1.3.4 Augmented reality vs. augmented virtuality

Referring to Figure 2, it is worth noting that there is no clear divider between AR and AV. This is because there is no definite known point where the ratio of reality/virtuality determines whether the MR system is AR or AV. In other words, there exists a theoretical “grey area” between AR and AV in which the world the user inhabits consists of both “real” and “virtual” objects and environments to such an extent that it is no longer possible to discern whether the world which the user inhabits is fundamentally “real” or “virtual” (Milgram & Kishino 1994; Milgram & Colquhoun 1999).

The closer MR systems get to reaching this grey area, the weaker the case becomes for using the terms AR and AV, as the distinction between them becomes less clear (Milgram et al. 1995). In the case of such a system, it would fall under neither category and simply be categorised as an MR system (Milgram & Colquhoun 1999). However, the details and discussion of this grey area fall under the realm of MR rather than VR and are thus out of the scope of this study.

2.1.3.5 Mediated reality

While AR and AV both aim to add to the viewer's reality (real or virtual), the term mediated reality describes technologies that aim to reconfigure or alter the viewer's reality, including augmenting, diminishing, or altering their reality (Mann 1999; Mann 2002; Grasset et al.

2005). A mediated reality system, or reality-mediator (RM), apart from providing the same functionality as an AR system, might hide certain objects from the viewer's environment (see Figure 6: Diminished reality systems can “remove” objects from the world by supplying the user with a modified video feed where an object has been replaced with appropriate background textures in real time (Kawai, Sato & Yokoya 2016:1) below) or might make them appear differently (Mann 1999). For example, it might use a video-based HMD to make the viewer's reality black and white except for certain objects, so as to place focus on them (Mann 1999).



Figure 6: Diminished reality systems can “remove” objects from the world by supplying the user with a modified video feed where an object has been replaced with appropriate background textures in real time (Kawai, Sato & Yokoya 2016:1)

Mediated reality can also refer to altering other sensory input, such as audio, for example by using audio signals that cancel out other audio signals using destructive interference, referred to as a “masking signal” (Elliott & Nelson 1993). This signal can be used in a listener's earphones to cover up and thus diminish incoming audio stimuli (Azuma 1997).

AR can thus be considered a subset of mediated reality, since mediated reality encompasses a range of modifications performed on a user's perception of reality, including augmenting, diminishing, and altering (Mann 1999; Mann 2002). This relationship is indicated in Mann's mediated reality Venn diagram (Mann 2002), as shown in Figure 7 below:

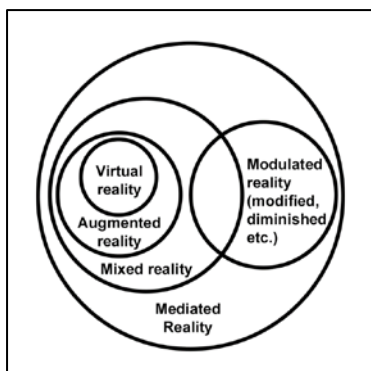


Figure 7: Mann's mediated reality Venn diagram (Mann 2002:2)

2.1.3.6 Mediated virtuality

Similar to how one can perform modifications on reality that lead to various types of mediated reality, the same holds for virtuality (Mann 2002). One can, therefore, create augmented, diminished, and modified virtuality using stimuli from reality, similar to how one can use virtual stimuli to augment, diminish, and modify reality (Mann 2002). Because of this, Mann (2002) proposes a continuum based on Milgram's "virtuality continuum" (Milgram & Kishino 1994), with "R" representing pure reality, the x-axis ("V") representing an increase in virtuality and the y-axis ("M") representing an increase in "mediality", as shown in Figure 8 (Mann 2002). A full discussion on the range of mediations and the applications thereof falls under the topic of mediated reality and virtuality and is thus out of the scope of this study.

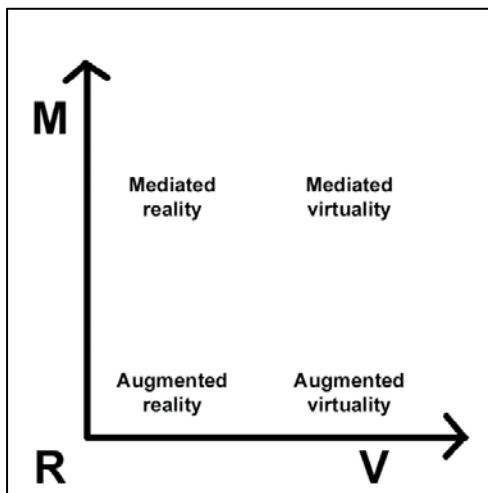


Figure 8: Mann's Reality, Virtuality, Mediality Continuum (Mann 2002:2)

2.1.3.7 Virtualized reality

Lastly, virtualized reality is identical to VR except for how the virtual content is created. While virtual content for VR is typically modelled digitally (using, for example, CAD software), virtualized reality refers to using real-world image data to create digital models (Kanade, Narayanan & Rander 1995; Kanade, Rander & Narayanan 1997). In other words, a real-world scene is captured and transcribed digitally to create a 3D model and viewpoints for the scene (Kanade, Narayanan & Rander 1995; Kanade, Rander & Narayanan 1997). This would allow a real-world event to be virtualized and then experienced by a user, including allowing the user to move around in the scene, by using an immersive display, such as an HMD (Kanade, Narayanan & Rander 1995).

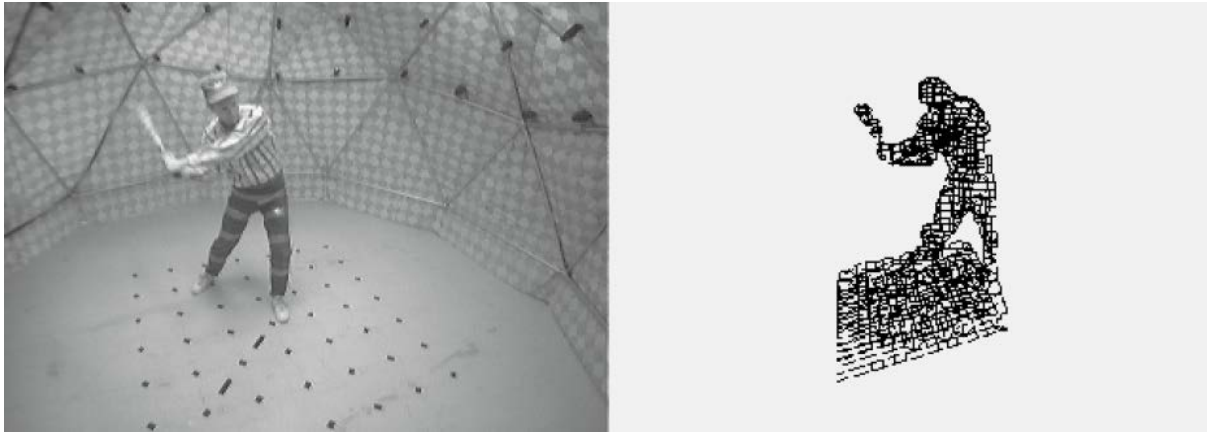


Figure 9: A dome with an array of cameras is used to capture and transcribe (virtualize) an event: a man swinging a baseball bat (Kanade, Rander & Narayanan 1997:13)

As this section has shown, the resurgence of VR has driven it from its “niche state” to a growing industry. The capability to combine reality and virtuality has also given rise to a number of related fields and technologies. The next section explores the use of VR in real-world application areas as well as the advantages and disadvantages that it offers.

2.2 Virtual reality application

VR has been used for a number of applications, including the following:

- space training (Loftin & Kenney 1995; Chen et al. 2015)
- vocational training (Fast, Gifford & Yancey 2004; Crison et al. 2005)
- surgical training (Meijden & Schijven 2009; Jordan et al. 2014)
- telerehabilitation (Popescu et al. 2000; Lucca 2009; Kairy et al. 2016)
- phobia therapy (Carlin, Hoffman & Weghorst 1997; Bowman & McMahan 2007; Morina et al. 2015)
- military training (Bowman & McMahan 2007; Peterson & Robertson 2013)
- pilot training (Satava 1993; Fast, Gifford & Yancey 2004; Peterson & Robertson 2013).

VR also has a brief and unsuccessful history in the gaming market of the 1990s, but the recent resurgence of VR technologies has caused many to predict that VR will soon become an integral part of the gaming market (Lee & Stewart 2016).

2.2.1 Application areas

The following section lists some of the areas where VR has successfully been used to improve systems, procedures, etc.

2.2.1.1 Space training

As mentioned in section 2.1.2.1, one of the earliest practical uses of VR was a system designed by NASA for training personnel for the Hubble Space Telescope (HST) repair and maintenance mission. The system was used to familiarise personnel with some of the HST components as well as to explore the viability of VR as a training tool in the future (Loftin & Kenney 1995). VR has also been used to simulate space motion sickness with the intent of identifying physiological factors that influence space motion sickness for use in pre-flight training (Chen et al. 2015).



Figure 10: This image from 1990 shows someone using the virtual interface environment workstation (VIEW), which included head-, hand- and body-tracking (Rosson 2014)

2.2.1.2 Vocational training

VR systems have been developed for training in fields such as welding (Fast, Gifford & Yancey 2004) and milling (Crison et al. 2005). Both applications are aimed at reducing the cost of training by replacing expensive machinery with high-fidelity VR training solutions (Fast, Gifford & Yancey 2004; Crison et al. 2005).

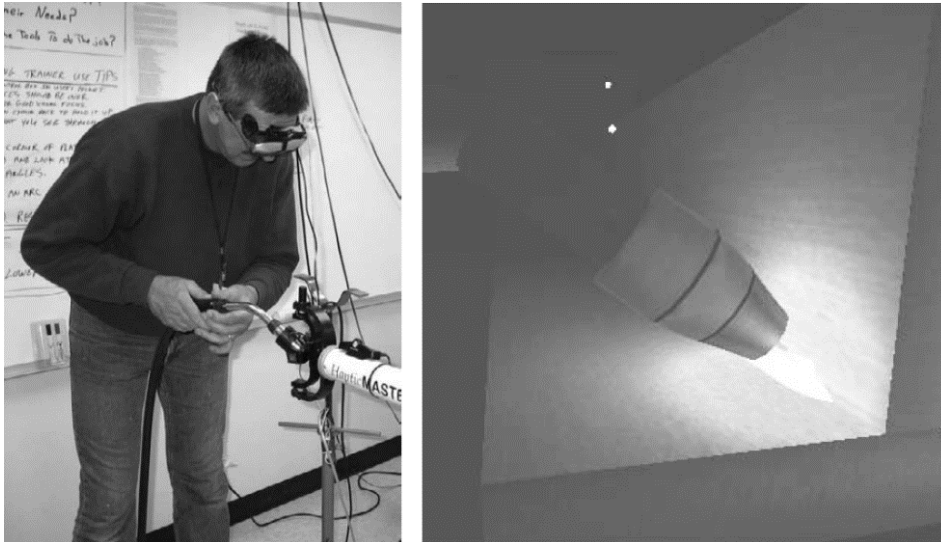


Figure 11: A person using a virtual welding system (left) and the virtual result (right) (Fast, Gifford & Yancey 2004:1)

2.2.1.3 Surgical training

Another early example of VR for training purposes is for surgical training, due to the necessity for surgeons-in-training to be able to practice dangerous procedures in a risk-free environment (Satava 1993). VR systems are used for training for conventional surgery (Jordan et al. 2014) as well as robot-assisted surgery (Meijden & Schijven 2009).

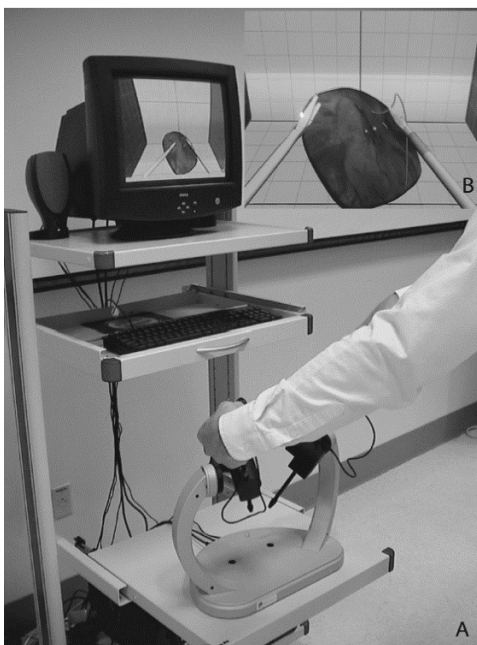


Figure 12: A person using the minimally invasive surgical trainer virtual reality (MIST-VR) system (Kanumuri et al. 2008:2)

2.2.1.4 Telerehabilitation

PC-based telerehabilitation allows patients to perform rehabilitative tasks that are usually performed at a clinic under the supervision of a therapist in the comfort of their homes (Popescu et al. 2000; Kairy et al. 2016). The use of VR has added benefits, such as the fidelity of the environment leading to increased mirror neurone activity (Lucca 2009) as well as providing intrinsic motivation to complete tasks at home (Kairy et al. 2016).



Figure 13: This VR telerehabilitation system lets users perform rehabilitative tasks at home while collecting data about their treatment (E-Health Reporter 2013)

2.2.1.5 Phobia therapy

VR systems can recreate situations and allow people with specific phobias to interact with those situations in a safe, private environment (Carlin, Hoffman & Weghorst 1997; Bowman & McMahan 2007). These scenarios can also be controlled and modified based on a patient's progress (Morina et al. 2015).

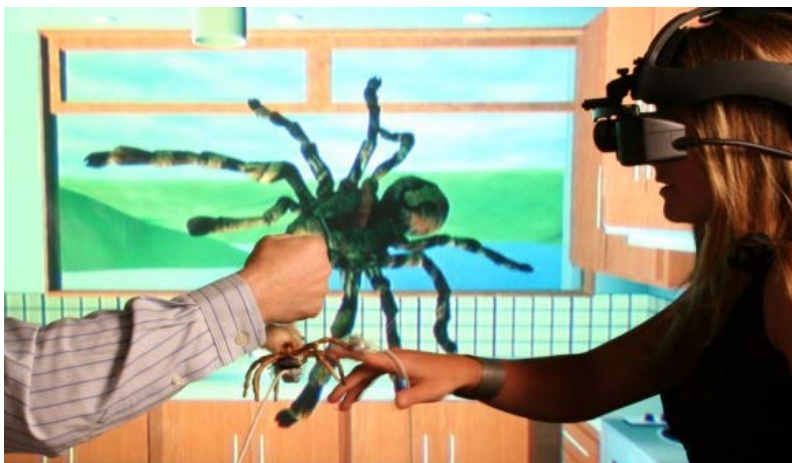


Figure 14: Combination of VR and a toy spider for the treatment of arachnophobia (Diezma 2016)

2.2.1.6 Military training

VR offers the potential to practice hands-on military training in a safe, simulated environment with much-needed realism and fidelity (Bowman & McMahan 2007). This approach is much cheaper than real-world exercises and has been shown to drastically decrease the number of errors made by military personnel (Bowman & McMahan 2007; Peterson & Robertson 2013).



Figure 15: Soldiers training with the dismounted soldier training system (Bymer 2012)

2.2.1.7 Pilot training

Although flight simulators predate VR (Satava 1993), the use of VR simulators has become an essential tool for pilot training, since it allows pilots to spend many hours “flying” before they ever set foot in an aircraft (Satava 1993; Fast, Gifford & Yancey 2004). VR simulators are speculated to have played a significant role in lowering the death toll of commercial flights since they were first used almost 40 years ago (Peterson & Robertson 2013).



Figure 16: A virtual reality system (left) that lets users fly a virtual helicopter (right) by interacting with a virtual cockpit (Yavrucuk, Kubali & Tarimci 2011:3, 5)

2.2.1.8 Gaming

The gaming industry also explored the potential to be present inside and interact with a VE with perhaps the most notable early example being the *VirtualBoy*, released by Nintendo in 1994 (Zachara & Zagal 2009). The *VirtualBoy* used a stereoscopic HMD and was aimed at revolutionising gameplay experiences by immersing players into their games (Boyer 2009). However, the *VirtualBoy* has since been regarded as one of Nintendo's biggest product failures, due to many factors, including the fact that the device was uncomfortable and only displayed the colours red and black (Boyer 2009; Zachara & Zagal 2009). Other companies like Sony and Sega also released VR-like gaming systems, which were also commercial failures (Boyer 2009; Zachara & Zagal 2009).



Figure 17: The Nintendo VirtualBoy (Schneider 2016)

As mentioned in section 2.1.2.2, there has been a recent resurgence in the VR consumer market with the release of multiple consumer HMDs, such as the Oculus Rift, HTC Vive, etc. (Cohen, Villegas & Barfield 2015). These have made major technological improvements over earlier HMDs (Desai et al. 2014; Xiao & Benko 2016). Because of these technological advances as well as newfound consumer interest in VR, it is estimated that the VR games market will become a multi-billion dollar industry within the next decade (Roettgers 2017; Grand View Research 2017; Jarvio, Wolf & Hardin 2018).

2.2.2 Advantages of virtual reality applications

VR offers several advantages in learning, training, and treatment environments, such as the ability to collect objective information about a user's interaction and skill level in the training environment, which can then be relayed via computer networks. For example, a telerehabilitation patient can perform rehabilitative tasks at home while a therapist monitors their interactions (Miner & Stansfield 1994; Peterson & Robertson 2013; Jordan et al. 2014).

Other advantages of VR for training environments include:

- allowing users to train even if the needed facilities (hardware, software, personnel) are not available or are too expensive (Miner & Stansfield 1994; Loftin & Kenney 1995; Seth, Vance & Oliver 2010)
- a low-risk environment for potentially dangerous training exercises (Satava 1993; Loftin & Kenney 1995; Peterson & Robertson 2013)
- control over objects/environments that might be difficult to control in real life, including scenarios that could become dangerous in real life (Carlin, Hoffman & Weghorst 1997; Morina et al. 2015)
- allowing for users/operators to “experience” scenarios, such as emergencies, to better prepare them for those scenarios in real life (Miner & Stansfield 1994; Morina et al. 2015)
- providing a more engaging experience for the user by providing feedback across more sensory modalities (Bowman & McMahan 2007).

An advantage of using VR for training (as opposed to non-VR computer-based applications) is that the user’s instinctive knowledge about the real (physical) world is transferred to their knowledge of interactions of manipulations in the digital “world” (Shaw et al. 1993; Seth, Vance & Oliver 2010). This is known as “training transfer” as their knowledge/training from the virtual environment is transferred to real-world scenarios (Bowman & McMahan 2007).

2.2.3 Disadvantages of virtual reality applications

One of the most prevalent problems with regards to the practical use of VR is that of motion sickness, specifically that caused by a simulator (Loftin & Kenney 1995; Curtis 2014). This is also known as simulator sickness (Kennedy et al. 1993; Loftin & Kenney 1995), VR sickness (Romano 2005), or cybersickness (Keshavarz et al. 2015). The most common symptoms of simulator sickness can be divided into three main groups (Kennedy et al. 1993; Loftin & Kenney 1995):

- **oculomotor symptoms:** such as eyestrain, blurred vision and headaches
- **disorientation symptoms:** such as dizziness and vertigo
- **nausea symptoms:** such as stomach awareness and burping.

Although simulator sickness has similar symptoms to motion sickness (Kennedy et al. 1993), simulator sickness is caused by a false perception of self-motion, which is called vection, while the user of the simulator is actually stationary (Curtis 2014). This false perception of self-motion leads to a mismatch between the input from the visual system and the vestibular

system (Bos, Bles & Groen 2008) as well as mismappings between other sensory faculties (Biocca 1999). Vection can be induced by the use of visual stimuli (Curtis 2014) as well as audio stimuli with the use of binaural audio, which is discussed in section 2.4.1.1 (Riecke, Feuereissen & Rieser 2009).

However, the relationship between vection and motion sickness, particularly visually-induced motion sickness (VIMS) is still highly debated as it is possible to experience vection without causing VIMS and is unclear whether vection is a requirement for VIMS (Keshavarz et al. 2015). Some medicines and techniques for preventing and mitigating the symptoms of motion sickness in VR have been proposed, such as medication, acupuncture, and hand-eye coordination tasks (Curtis 2014). Despite this, motion sickness still threatens to limit the amount of time a susceptible user can spend in a VE, especially with the use of an HMD (Curtis 2014).

Another limiting factor in the practical use of HMDs is the size of the field-of-view (FOV). A person's FOV is normally slightly larger than 180° (Xiao & Benko 2016), whereas these are the FOVs provided by the following HMDs:

- **Oculus Rift:** $\pm 90^\circ$ (Xiao & Benko 2016)
- **HTC Vive:** $\pm 110^\circ$ (<https://www.htcvive.com/us/product/>)
- **Samsung GearVR:** $\pm 96^\circ$ (<http://www.samsung.com/global/galaxy/wearables/gear-vr/>).

Although a larger FOV is found to correlate with many desirable results, such as increased immersion, presence, and memory, it has also been found to increase simulator sickness in the wearer (Lin et al. 2002). This means that designers of HMDs face a difficult trade-off when creating HMDs for VR (Xiao & Benko 2016).

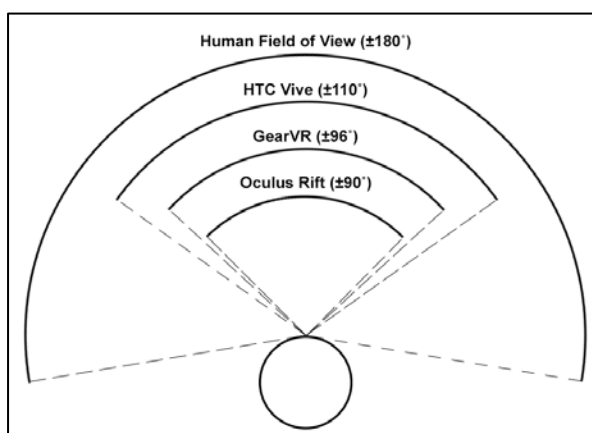


Figure 18: Field of view for the average person (Xiao & Benko 2016) compared to different HMDs

Other technical difficulties that HMDs face are the “screen door effect” and “ghosting”. The screen door effect refers to a perceived black grid that the viewer perceives because of empty spaces between pixels while ghosting refers to blurring caused by the switching time of the pixels in the display compared to the movement of the user’s head (Desai et al. 2014).

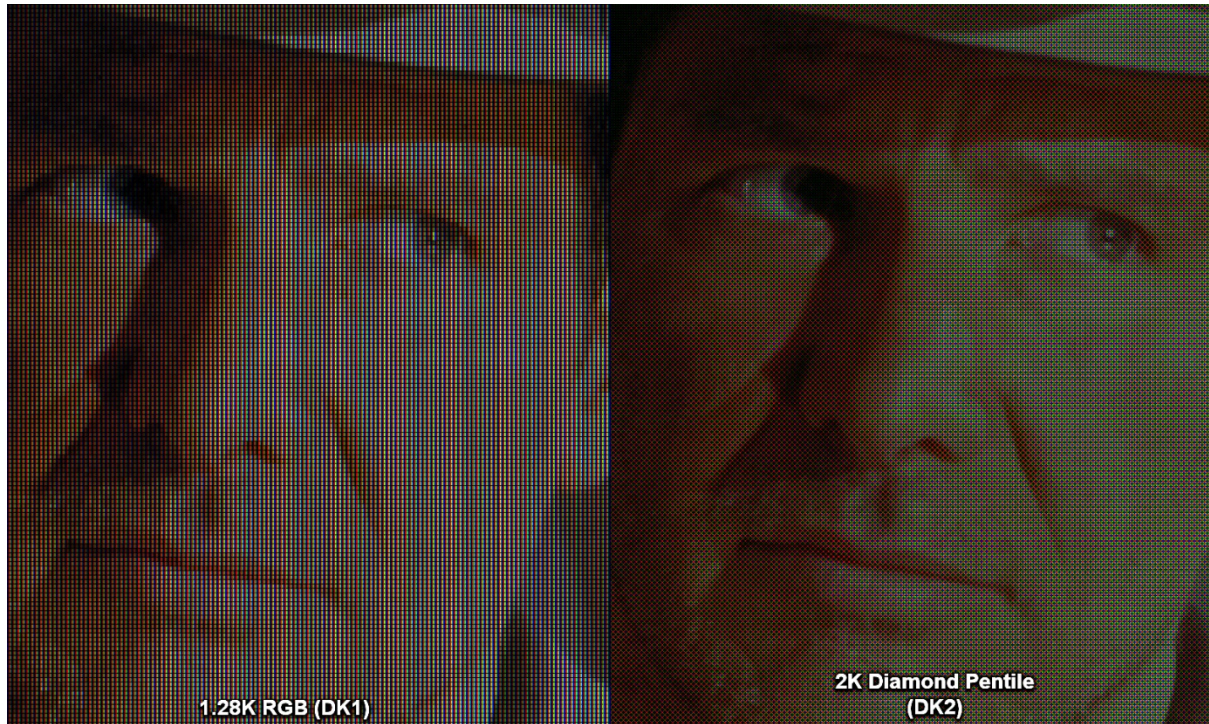


Figure 19: The screen door effect in the display of the Oculus Rift DK1 (left) and DK2 (right) (Desai et al. 2014:2)

This section has shown some real-world applications of VR as well as the advantages and disadvantages of its use. The next section discusses two terms that are crucial in understanding VR on both a technical and conceptual level: immersion and presence.

2.3 Immersion and presence

The sensation of “being there” in the VE is often listed as being an important part of VR (Bowman & McMahan 2007). This concept is often described with the terms “immersion” and “presence”, the precise definitions and relationships of which are often confused, misunderstood, or used synonymously (Regenbrecht, Schubert & Friedmann 1998; Slater 2003). This section explores each of these terms, their relationships, their impact on VR, and other related concepts.

2.3.1 Immersion

Immersion has been defined in different, often contradictory ways (Witmer & Singer 1998; Slater 1999) and has been used interchangeably with the term *presence* (Regenbrecht, Schubert & Friedmann 1998). This section determines a definition of immersion to be used for the remainder of the study and investigates the aspects that determine immersion as well as the effects thereof.

2.3.1.1 Defining immersion

To be immersed, in an everyday context, refers to being deeply mentally involved in something to such an extent that one's attention and mental faculties are removed from one's everyday environment and focused entirely on a task/activity (Oxford 2018c; Cambridge 2018b; Oxford 2018d). It can also refer to placing a person or object in liquid so that they are entirely surrounded by it (Oxford 2018c; Cambridge 2018b; Oxford 2018d). Thus, displays that use technologies that "surround" the user and attempt to remove them from their everyday environment and only provide information or stimulation from the VE are usually called immersive displays (Earnshaw, Gigante & Jones 1993; Heineken & Schulte 2007). For this reason, many studies simply use the term immersion to refer to isolating one or more users from their natural reality when using a VR system (Brooks 1999; Heineken & Schulte 2007). In this case, a VR system that isolates the user is described as being "immersive" as opposed to being "non-immersive" (Brooks 1999; Heineken & Schulte 2007).

However, a broader definition of immersion in VR refers to a measurable quality of the VR system (Slater, Usoh & Steed 1995; Bowman & McMahan 2007). Immersion, as defined by Slater, Usoh and Steed (1995), refers to an objective measure of the system that delivers VR to the user, which exists completely separate from any subjective experiences by the user (Slater, Usoh & Steed 1995). This definition builds on earlier work by Slater and Usoh (1993), which did not explicitly refer to this measurable quality as immersion, but rather as "external properties of immersive virtual environments" (Slater & Usoh 1993; Slater, Usoh & Steed 1995). This definition of immersion has since been widely adopted and used by other studies on immersion and presence (Bystrom, Barfield & Hendrix 1999; Bowman & McMahan 2007).

Although other definitions for immersion have been used, including more subjective approaches (Witmer & Singer 1998), this study focuses on Slater's definition of immersion as an objective quality, as well as revisions or refinements thereof, for the following reasons:

- It separates the quantifiable aspects of the VR system from the subjective qualities of the user(s) using the system (Slater 1999).

- It is measurable by evaluating the various aspects that determine immersion, as discussed in section 2.3.1.2 (Slater 1999).

These are both desirable reasons, because, as discussed in more detail in section 2.3.1.3, there is a correlation between immersion and presence (Slater 1999). This means that using the definition of immersion as an objective and quantifiable measure, as an independent variable as such, allows one to use immersion as a measuring tool for the amount of presence experienced in a system (Slater 1999; Bowman & McMahan 2007).

Thus, for this study, immersion in VR is defined as the total of a set of objectively quantifiable aspects of the sensory output that the system delivers using displays, such as audio, visual, and haptic (Regenbrecht, Schubert & Friedmann 1998; Bystrom, Barfield & Hendrix 1999; Slater 2003). It is therefore not a binary quality of a system (i.e. immersive/non-immersive), but a continuum of measurable qualities that exist separately from their subjective perception by a user (Slater 1999; Diemer et al. 2015). These aspects of the hardware and software of a system add up to deliver mediated stimuli to the user (Regenbrecht, Schubert & Friedmann 1998).

2.3.1.2 Aspects of immersion

Using the definition of immersion as objective and quantifiable, it follows that one can measure the level of immersion that a system provides by individually measuring the factors that make up immersion (Slater & Wilbur 1997). There have been many attempts to identify all of these factors, including using broad descriptors, such as vividness, inclusion, etc. (Slater, Usoh & Steed 1995) as well as more technology-specific factors, including software factors such as frame rate, refresh rate, realism of the environment, etc. (Bowman & McMahan 2007) and hardware factors such as the FOV and size/weight of the HMD (Slater & Wilbur 1997; Bowman & McMahan 2007).

The approach of the current analysis of the literature is to first consolidate a list of high-level factors and then match low-level (hardware/software specific) factors to these high-level factors. As a starting point, the current analysis of the literature focuses on the list that accompanies the definition of immersion as defined by Slater, Usoh and Steed (1995). According to this study, the extent to which a VR system is immersive is determined by whether it can deliver a VE that is (Slater, Usoh & Steed 1995):

- **inclusive:** the extent to which the system isolates the user from the real environment around them
- **extensive:** the number of modalities for which a system provides feedback/stimuli
- **vivid:** the quality and fidelity of sensory feedback across all modalities
- **surrounding:** the extent to which a display is panoramic in three dimensions.

Additionally, the system should provide matching feedback, which refers to the extent that the user's behaviour/controls in the real environment corresponds to appropriate feedback in the VE (Slater, Usoh & Steed 1995).

Earlier work by Slater and Usoh (1993) also lists "vividness" and "correspondence of virtual body to real body", which is similar to the notion of "matching feedback", as external properties of immersive virtual environments (IVEs), although the study does not make explicit use of the term "immersion" (Slater & Usoh 1993). The study also includes aspects not included in the aforementioned list, such as:

- consistency of representation
- interactivity
- simplicity of connections between actions and effects.

A number of other studies have listed similar concepts as factors that determine immersion. Although Steuer (1992) does not use the term "immersion" either, the study lists two main aspects that determine "telepresence", which, as discussed in section 2.3.2.1, can be used interchangeably with presence (Lessiter et al. 2001). The study further states that these aspects only refer to the technology itself and not to the subjective perception of them by a user, which aligns with the definition of immersion as defined by Slater, Usoh and Steed (1995). Both of these high-level aspects include multiple lower-level factors (Steuer 1992):

- **Vividness:** the sensorial richness of the VE, including:
 - the number of sensory channels for which stimulation is provided
 - the quality/resolution within each channel. It should be noted that the study does not equate vividness to realism, but rather to sensorial richness.
- **Interactivity:** how well the VE allows users to interact with it, including:
 - the rate at which the VE processes input from the user
 - the number of possible interactions that the VE provides the user
 - how naturally/unnaturally the input from the user maps to actions within the VE.

Lombard and Ditton (1997) only list the number of sensory modalities and the degree to which the system isolates the user from external stimuli as measures for immersion, but list a number of other factors as "causes of presence", such as (Lombard & Ditton 1997):

- consistency and fidelity/three-dimensionality of visual display characteristics
- interactivity, which includes:

- the number of inputs
- the number of characteristics that can be modified
- the degree to which users can control the attributes of the VE experience
- the degree of correspondence between the user input and system response
- the response speed of the system
- the obtrusiveness of the medium, i.e. the degree to which the system draws attention to itself or is distracting
- whether or not the system allows users to use voice commands to interact with the VE.

The study also lists specific content-related aspects of a VE, such as the number of people (real or virtual) in the VE and whether or not the events in the VE are unfolding in real-time as opposed to being “recorded” (Lombard & Ditton 1997). However, as is discussed in section 2.3.2.2, this study considers aspects that are related to the content rather than the form of the system to be more closely related to “involvement” than immersion (Slater 2003).

Slater and Wilbur (1997) build on the same aspects from previous work (Slater, Usoh & Steed 1995), but add consideration for a self-contained “plot” that includes interactions and responses from the environment as a measure of immersion (Slater & Wilbur 1997). This study also treats this as a content-factor rather than a form-factor and is thus more closely related to involvement (Slater 2003). Regenbrecht, Schubert and Friedmann (1998) divide the list into two groups of factors:

- regarding the visual stimuli:
 - fidelity
 - resolution
 - extractability of cues for three-dimensionality
 - FOV
 - symbolic, geometric and dynamic information
- properties of the hardware:
 - the weight of the HMD
 - cables that may distract the user.

Although, as mentioned earlier, the current analysis of the literature only focuses on definitions of immersion as an objective quality, the study by Witmer and Singer (1998), which describes immersion as a subjective experience, also includes some determining factors that are similar to those in other studies, such as:

- isolation from the physical environment

- the ability for the user to interact with their environment in a natural way.

Another study that does not use the term immersion, but still lists factors that are similar to established immersion-factors is that of Biocca (1999). This study uses the term “sensory engagement” to describe the extent to which the user’s senses are engaged/connected to the device and lists the following as determining factors (Biocca 1999):

- the number of sensory channels that are engaged by the system
- sensory fidelity
- the extent to which the system engages the user’s sensory channels and suppresses external stimuli (which the study refers to as sensory “saturation”).

Sheridan (2000) notes four attributes that are expected to have major effects on the overall quality of VR experiences, the first three of which are attributes of the system and the last one a subjective reaction to these attributes, which, since it does not fall under the quantifiable aspects of the system, is discussed as part of presence rather than immersion. The first three attributes are as follows:

- **Information quantity, or the number of bits in the display:** measurable attributes of the various displays, such as the visual, audio, and haptic displays’ refresh rates, visual pixels, etc.
- **Sensor position/orientation relative to the sensed object:** changes in perception caused by moving around in the environment, for example, moving one’s head causing a change in image.
- **Ability to change the relative location of manipulated objects:** being able to enact changes on the environment, such as moving objects around with various interaction mechanisms.

As discussed in section 2.3.2.2, the last of these attributes also falls under a cause of presence known as environmental presence, rather than immersion.

Slater (2003) adds to previous work by adding tracking coverage and behavioural fidelity, i.e. the extent to which any virtual person/character behaves like a human, to the list of immersion factors (Slater 2003). Bowman and McMahan (2007) build on the work of Slater (2003), but focuses on visual immersion and lists the following as visual immersion factors:

- FOV
- field of regard (the size of the visual field surrounding the user)
- display size and resolution
- stereoscopy

- head tracking
- realism
- frame/refresh rate.

Although some studies equate the notion of “vividness” with that of “realism” (Witmer & Singer 1998), in the definition of vividness as defined by Steuer (1992) it is stressed that it does not necessarily refer to resembling real-world objects (Steuer 1992). The realistic resemblance of virtual stimuli to their real-world counterparts might sometimes be desirable, for example when using VR for phobia treatment to trigger fear responses (Bowman & McMahan 2007). However, others have found that not only is a realistic representation of a VE not required for a sense of believability (Slater et al. 2006), but in some cases the very lack of realism/verisimilitude might even help enforce the illusion of being “present” (Biocca, Kim & Choi 2001). For those reasons, the current analysis of the literature does not consider vividness to correlate with realism or verisimilitude, but rather with the quality and richness of the various display technologies and thus treats vividness and realism as separate qualities.

The following list builds on the original list by Slater, Usoh and Steed (1995) as consolidated by Bystrom, Barfield and Hendrix (1999) and joins all the factors above into six high-level factors:

- **Inclusive/occlusion/isolation/saturation:** the extent to which the system ensures that the user only receives sensory stimuli about the VE (Slater, Usoh & Steed 1995; Lombard & Ditton 1997; Bystrom, Barfield & Hendrix 1999; Biocca 1999). This includes avoiding “distraction factors” that arise from technical qualities of the system (Slater & Wilbur 1997).
- **Extensive:** the number of sensory modalities that the system provides sensory stimulation for (Slater, Usoh & Steed 1995; Bystrom, Barfield & Hendrix 1999; Biocca 1999).
- **Surrounding/panoramic/field of regard:** the extent to which the stimuli surrounds the user (Slater, Usoh & Steed 1995; Bystrom, Barfield & Hendrix 1999; Bowman & McMahan 2007).
- **Vivid/fidelity:** the quality of displays resulting in richness of sensory stimuli in all modalities (Slater, Usoh & Steed 1995; Regenbrecht, Schubert & Friedmann 1998). Vividness also refers to the “fidelity” of the behaviour of social beings inside the VE (Slater 2003).
- **Matching/interactivity:** the current study groups together the notion of system interactivity as defined by Steuer (1992) and matching between user input and system response as defined by Slater, Usoh and Steed (1995). This includes all factors that relate

to how naturally the user can interact with the VE and any factors that aid or hinder this interaction (Steuer 1992; Slater, Usoh & Steed 1995; Slater & Wilbur 1997).

- **Egocentric virtual body representation:** the extent that the VE orients the user’s self-representation not around an abstract point in space, but around a virtual body which becomes the central point from which all perception takes place (Slater & Usoh 1993; Slater & Wilbur 1997; Bystrom, Barfield & Hendrix 1999). The sensory stimuli from the VE are thus perceived as if the user were inside the VE at that specific location (Slater & Usoh 1993; Sheridan 2000).

The following table is a non-exhaustive list that aligns all the aforementioned lower-level aspects of immersion with their corresponding high-level factors:

Table 2: Lower-level aspects of immersion divided according to their higher-level aspects

Inclusive	Extensive	Surrounding	Vivid	Matching	Egocentric
Effectively blocks out external stimuli across all senses (Slater 2003) “Distraction factors” (Slater & Wilbur 1997), including: •weight of HMD (Regenbrecht, Schubert & Friedmann 1998) •distracting cables (Regenbrecht, Schubert & Friedmann 1998).	Number of senses that feedback is provided for (Slater 2003)	FOV (Bowman & McMahan 2007) Head-tracking range (Slater 2003)	“Behavioural fidelity” (Slater 2003) Resolution (Regenbrecht, Schubert & Friedmann 1998) Three-dimensionality (Regenbrecht, Schubert & Friedmann 1998) Stereoscopy (Bowman & McMahan 2007) Representation consistency (Lombard & Ditton 1997)	Ability of the system to allow “natural” interaction (based on user’s internal representation systems) (Bystrom, Barfield & Hendrix 1999) Range of interactions which the system caters for (Steuer 1992) Latency between user input and system output (Slater & Wilbur 1997; Bowman & McMahan 2007)	Sensory output from VE is perceived from a point in virtual space. This includes (Slater & Usoh 1993): •visual point of view •auditory location •kinaesthetic frame of reference.

Thus, it follows that the level of immersion of a system can be defined as the inclusion and/or measurement of these factors, among others, that aid or hinder immersion in a system.

2.3.1.3 Benefits of immersion

A number of benefits of immersion in VR have been identified, such as:

- increased spatial understanding for 3D environments (Bowman & McMahan 2007; Schuchardt & Bowman 2007)
- improved task performance (Narayan et al. 2005; McMahan et al. 2006; Bowman & McMahan 2007)
- decrease in performance time (McMahan et al. 2006).

Immersion also has the potential benefits of reducing the amount of visual information clutter to increase the comprehensibility of information as well as the potential to increase the bandwidth of useful information in VR (Bowman & McMahan 2007).

However, since immersion is not a binary quality and depends on many individual factors of a system, the issue of identifying the benefits of immersion becomes quite complicated, since different aspects of immersion can have different benefits in different contexts (McMahan et al. 2006). For example, in one study where users had to collaborate in a shared VE to complete object manipulation tasks, it was found that stereoscopy significantly contributed to the task performance (Narayan et al. 2005), whereas another study did not find a significant correlation between stereoscopy and task performance when users performed different object manipulation tasks alone in a VE (McMahan et al. 2006). Thus, attempting to quantify the advantages of immersion in a system depends on not only the aspects of immersion that a system may or may not possess, but also the interplay between them and the context-specific details of the task being performed (McMahan et al. 2006; Bowman & McMahan 2007). However, the study of each of these factors' effect on task performance, completion time, etc. is out of the scope of this study.

Apart from these direct benefits, immersion has a more indirect, but vital benefit in the context of VR: an increase in presence (Slater 2003; Bowman & McMahan 2007; Diemer et al. 2015).

2.3.2 Presence

As mentioned in section 2.1, presence is such an important part of VR that the very definition of VR is tightly linked with that of presence. Presence, sometimes referred to as “telepresence” (Steuer 1992; Lessiter et al. 2001), is often simply defined as the illusory perception that a person entering a VE is really “there”, in other words, they are “present” in the VE (Steuer 1992; Lowood 2015). However, the definition reaches further than that and, as is discussed in the next section, is not limited to VR (Lombard & Ditton 1997). Understanding the concept

of presence is vital for creating useful VR applications and experiences and has many advantages (Lombard & Ditton 1997). The following section focuses on definitions of presence that extend the simplified definition of “being there” put forth by many studies on VR.

2.3.2.1 Defining presence

VR aims to create the illusion that the environment that surrounds the user is not only real, but the user is also inside the environment as a separate entity that can interact with and modify the environment (Heeter 1992). The process of discerning your presence in a VE is thus similar to the process of discerning your presence in the real world, which partially relies on the user’s ability to differentiate themselves from the environment as a separate, but real being that is a part of the synthesized environment (Heeter 1992; Regenbrecht, Schubert & Friedmann 1998; Heeter & Allbritton 2015).

A large part of experiencing presence is thus experiencing a VE that responds to the user as if it were a real environment that forms part of the user’s everyday reality and that the user is physically located at and interacts with that environment through a virtual body (Slater & Wilbur 1997; Regenbrecht, Schubert & Friedmann 1998; Lessiter et al. 2001). Although this illusion is important for experiencing presence, it is not in itself the definition of presence (Slater 2003). Presence is also not a binary quality, but rather a spectrum (users of VR might experience higher or lower levels of presence) (Slater 2003), the determinants and impacts of which are discussed in sections 2.3.2.2 and 2.3.2.4.

Another important concept for the definition of presence is that of a *mediated* experience. A user experiencing presence in a VE feels that their experience of the environment is *unmediated*, i.e. that they are receiving sensory stimuli and interacting with the environment directly, even though all the input and output is being delivered using VR hardware and software (Steuer 1992; Lombard & Ditton 1997). This notion of a mediated experience can be generalised to a wider range of electronic devices, for example, the way television viewers feel (to a lesser extent than VR users) that they are transported to the world the television creates (Lombard & Ditton 1997). It can even be compared to the way a telephone creates a sense of being in the unmediated (physical) company of the person one is talking to, similar to Heeter’s notion of “social presence”, which is discussed in section 2.3.2.2 (Heeter 1992; Lombard & Ditton 1997).

Thus, presence also involves the illusion that a user is having an unmediated experience of an environment, while they are actually having a mediated one (Lombard & Ditton 1997; Regenbrecht, Schubert & Friedmann 1998). However, this does not mean that the user is

unable to discern the real world from the virtual one, but rather that the user is enacting an “active suspension/suppression of disbelief”, in other words, they are adapting to a cooperative frame of mind (Slater & Usoh 1993; Lombard & Ditton 1997; Sheridan 2000). In other words, the user consciously knows that they are not physically inside the VE, but their internal systems, such as their perceptual, vestibular, and proprioceptive systems, might react in a similar way as if they were present in the VE (Regenbrecht, Schubert & Friedmann 1998; Slater 2003). This compels them to behave in a similar way as they would, were they really transported to the world portrayed by the VE (Regenbrecht, Schubert & Friedmann 1998; Slater 2003). Their egocentric self-representation, i.e. their virtual body, thus “becomes” their body and allows them to act naturally in VR through their virtual body (Slater & Wilbur 1997). In other words, there exists a tight coupling between their body schema (their internal body representation) and their virtual body representation (Biocca 1999). This concept of “becoming” one’s virtual self through a tight coupling of user actions and system feedback to “enter” a VE is a defining factor of VR since it differentiates VR from other media that also incorporate a VE (Steuer 1992).

Since the user’s perception of presence is tied to their virtual “self” in VR, presence manifests itself as a state of consciousness (Steuer 1992; Slater & Wilbur 1997). This means that the causes and effects vary from person to person (Steuer 1992; Lombard & Ditton 1997) and the same objective factors can lead to different subjective experiences in different users (Slater 2003). Presence manifests itself in a user’s mind in two ways (Slater & Wilbur 1997):

- **Subjectively:** this refers to the user’s sense of “being there”, i.e. the extent to which the user experiences a VE as “place-like”.
- **Objectively:** this refers to the extent to which a user behaves similarly in VR as they would in their everyday reality.

This experience of an illusory unmediated experience, although it is involuntary and may even surprise a VR user, is also a natural reaction to a VR experience (Regenbrecht, Schubert & Friedmann 1998). This might be because all of our experiences in our everyday world, although they seem unmediated, are actually mediated by our sensory organs and mental faculties that process them and construct a mental model of our environment from these stimuli (Loomis 1992; Regenbrecht, Schubert & Friedmann 1998). This unconscious ability to attribute external phenomena, i.e. occurring “outside” oneself, to external objects and environments is known as *distal attribution* and is closely related to the concept of presence (Loomis 1992; Auvray et al. 2005). Thus, presence also involves building a mental representation of the environment and reflecting on that model to make it one’s temporary

reality, similar to how we unconsciously construct a model of reality on a daily basis (Loomis 1992; Regenbrecht, Schubert & Friedmann 1998).

Thus, for the purposes of this study, presence is defined as an involuntary state of consciousness whereby a user of VR uses immersive stimuli to construct a mental representation of a VE, including a virtual body which “becomes” their body in VR. The user enacts a degree of suspension of disbelief to invoke the illusion that they are having an unmediated experience of the surrounding environment, although they are at all times consciously aware that they are not physically located in this environment. The result of this experience is that they feel physically “present” inside the VE.

2.3.2.2 Causes of presence

As already mentioned, immersion is often cited as one of the main causes of presence (Lessiter et al. 2001; Slater 2003; Bowman & McMahan 2007). However, since immersion is a multifaceted concept with different aspects bearing different weight in different contexts (Steuer 1992; Slater 2003), this causal relationship is quite complex and thus needs to be examined in more depth.

Heeter and Allbritton (2015) build on earlier work by Heeter (1992) and list four dimensions of presence in VR that relate to different aspects and causes of a VR experience:

- **Personal presence:** comes from the user’s perception of their body in VR as well as being able to control it.
- **Social presence:** comes from other social beings in the VE who react to the user’s actions.
- **Environmental presence:** comes from the reaction of the virtual environments and objects to the user’s actions.
- **Embodied presence:** comes from the user paying attention to and reacting to emotions and feelings so as to connect to their sense of self; this concept stems from the notion of “introspection”, which refers to being aware of physical sensation, such as temperature or pain, in the real or virtual world.

As already discussed, Sheridan (2000) also lists being able to enact changes on the virtual environment as a major contributor to a VR-experience, although this is purely motivated by stating that it would make the VR seem more realistic (Sheridan 2000). Lombard and Ditton (1997) list two ways in which a user can experience illusory non-mediation: either the medium through which the user experiences VR must become “invisible” so as to function as an open window that allows the user to “see into” the VE or the medium itself must be transformed into a social entity. They also list three types of variables that are the main causes

of presence for each of these conditions that are similar to determinants of presence as listed by Lessiter et al. (2001):

- **Media user variables:** qualities of the user that influence their levels of presence experienced.
- **Content variables:** what content/narrative the system delivers to the user.
- **Form variables:** pertain to the form factors, i.e. the qualities of the system itself that enhance presence. For the current study, this is identical to the notion of immersion.

These causes are found in other studies as well. Slater (2003) also lists modelling reality as close as possible as a possible method to achieve presence but goes on to suggest that designers of VR could also determine which aspects of perception contribute more to our perception of reality so as to be able to deliver presence in systems with low levels of immersion (Slater 2003). Lombard and Ditton's (1997) notion of an open window which allows a user to see into VR is once again similar to the notion of distal attribution, which relies heavily on the user's ability to grasp the linkage between their actions and the results in the (possibly virtual) environment (Loomis 1992; Auvray et al. 2005). This either happens because the linkage is natural/transparent or because the user has learned the linkage through training (Loomis 1992; Auvray et al. 2005). This is also similar to Heeter's notion of personal presence through being able to control one's own body in VR (Heeter 1992) and is related to the notion of integrating input from different sensory modalities to construct a mental model of the environment to enhance the feeling of presence (Regenbrecht, Schubert & Friedmann 1998; Biocca, Kim & Choi 2001).

This is supported by Zahorik and Jenison (1998) who stress the importance of the mapping of user action to environment outcome (which their study calls "successfully supported actions"), similar to the notion of a perception-action link (Zahorik & Jenison 1998; Lessiter et al. 2001). The former study, however, not only lists successfully supported actions as a strong determinant of presence but rather as the only determinant, although it should be stressed that the former study takes a purely philosophical rather than an empirical route to reach this conclusion (Zahorik & Jenison 1998). Nevertheless, the study makes another useful contribution to the current discussion, namely the concept of a "lawful" response to a user's action by a virtual environment (Zahorik & Jenison 1998). This is defined as a response that is similar to what a user would expect based on their experience with their everyday environment (Zahorik & Jenison 1998).

It has also been widely suggested that other social beings in VR should enhance the feeling of presence, since we are used to encountering other social beings in our everyday lives (Steuer

1992). Similar to Heeter's notion of social presence (Heeter 1992), Slater and Wilbur (1997) emphasise the need to be able to communicate with other inhabitants of the VE, who should then be able to respond (Slater & Wilbur 1997). Biocca (1999) goes as far as to list this as a form of presence on its own, as opposed to other forms of presence stemming from feeling physically "there" and feeling a connection to one's virtual body (Biocca 1999). Nowak and Biocca (2003) use these other types of presence (listed as social presence and co-presence) and emphasise that although virtual avatars can increase presence, there are many factors regarding the representation of avatars that contribute to the levels of presence that these avatars induce. It is also possible that a reason why social interactions increase the level of presence is an extension of Zahorik and Jenison's (1998) notion of successfully supported actions. In other words, when we interact with social beings in VR and they respond in a way that aligns with our expectation of how social beings would behave in the real world, it generates a lawful response from the environment, which enhances presence (Zahorik & Jenison 1998). Furthermore, it has been suggested that a user's presence can stem not only from interaction with other social beings in VR but also from perceiving the medium/system itself as a social being (Lombard & Ditton 1997). However, since social interaction in VR is neither a simple matter of discussion nor the focus of the current study, it is outside the scope of the current study.

The level of presence experienced is also affected by users themselves (Steuer 1992) with both the user's physical and mental attributes as well as demographic factors affecting the level of presence experienced (Biocca 1999; Fox, Bailenson & Binney 2009). For example, gender has been found to influence the level of presence experienced, with men experiencing higher levels of presence than women, due to several factors, such as previous computer and gaming experience as well as spatial ability (Felnhofer et al. 2012). Other user attributes that affect presence include a user's willingness to suspend disbelief, their previous experience(s) with VR, their ability to integrate multisensory system output, and their psychological and emotional traits (Lombard & Ditton 1997; Biocca, Kim & Choi 2001; Lessiter et al. 2001; Riva et al. 2007). However, since an investigation into the individualised factors that influence presence would involve psychological and physiological study, a detailed discussion of the impact of each of these factors on presence is outside the scope of this study.

Since a detailed discussion regarding form factors, i.e. immersion, has already taken place, this section does not discuss the matter further, except for discussing the influence of form factors on VR sickness. As discussed in section 2.2.3, one of the main causes of VR/simulator sickness is a conflict between the information received by different senses, which is referred to as intersensory conflict (Biocca 1999). One of the causes of intersensory conflict is a poor

level of synchronisation between user input and system output, i.e. system lag (Biocca 1999), which may have a direct influence on presence, as VR sickness has a negative impact on presence (Witmer & Singer 1998). Thus, synchronisation, apart from being an aspect of immersion, also affects presence directly by affecting VR sickness in a system (Witmer & Singer 1998; Heineken & Schulte 2007). However, the cause-effect relationship between presence and VR sickness is complicated as presence is often suggested as playing a role in causing VR sickness (Lombard & Ditton 1997; Keshavarz et al. 2015), which is discussed further in section 2.3.2.4.

As mentioned before, this study considers certain aspects of a VE, such as the number of people in the VE and whether events are “pre-recorded” or unfolding in real time, to form part of content/narrative factors (Slater 2003). In other words, they have to do with what the system delivers rather than with the system itself (Slater 2003). Content factors affect presence by increasing or decreasing the amount of “involvement” experienced, which refers to the amount of attentional resources that a user allocates to the experience (Witmer & Singer 1998; Lessiter et al. 2001). However, although involvement is often confused or equated with presence, the two concepts are separate, since one can be involved in an activity, but not be present and vice versa (Slater 2003). For example, one could have a strong sense of physical presence in a virtual location, but be bored or uninterested by its contents (Slater 2003). Nevertheless, involvement is often listed as having a positive influence on presence (Witmer & Singer 1998; Lessiter et al. 2001) as it lets the user allocate more attentional resources to the experience. This encourages an enhanced suspension of disbelief (Bystrom, Barfield & Hendrix 1999; Lessiter et al. 2001), similar to the concept of intense concentration and enjoyment known as “flow theory” (Csikszentmihalyi 1997; Bystrom, Barfield & Hendrix 1999). An enhanced focus on certain parts of the experience can also encourage an enhanced suspension of disbelief by lessening focus on other parts of the experience which might otherwise cause disbelief (Sheridan 2000).

The next section investigates how the level of presence experienced by a user can be measured.

2.3.2.3 Measuring presence

Presence measurements are generally divided into two categories: objective and subjective (Zahorik & Jenison 1998). Objective measurements refer to measurable attributes of the user that change depending on the level of presence experienced (Zahorik & Jenison 1998). This includes physiological or behavioural properties, as well as any measurable qualities about the VE, such as task performance times (Regenbrecht, Schubert & Friedmann 1998). User attributes that can be used to measure presence can be broadly categorised into two types:

physiological attributes and behavioural attributes (Lombard & Ditton 1997). Physiological attributes refer to physiological changes in the user that are a direct result of presence experienced, such as changes in heart rate, blood pressure, etc. (Lombard & Ditton 1997). Behavioural attributes refer to how a user's behaviour is influenced as a result of experienced presence, specifically measuring whether users react similarly to situations in VR as they would in a similar real-world scenario (Regenbrecht, Schubert & Friedmann 1998; Slater 2003). For example, if a user's reflexes cause them to duck for a virtual ball approaching their virtual head, this can be taken as an indicator of presence (Lombard & Ditton 1997; Regenbrecht, Schubert & Friedmann 1998).

Potential problems with using these objective measures include (Regenbrecht, Schubert & Friedmann 1998):

- the extra setup or technology needed to measure physiological responses
- their inability to work for certain situations (for example, one can only measure task performance time in certain VEs)
- the difficulty of comparing results for different VEs because different VEs might provide different features that could skew the results.

Subjective measurements for presence usually take the form of questionnaires (Regenbrecht, Schubert & Friedmann 1998), but can also take the form of other qualitative tools, such as interviews (McCall, O'Neil & Carroll 2004). These tools aim to measure the amount of presence felt by a user inside an environment and often relies on a rating scale to describe the level of presence measured (Zahorik & Jenison 1998). A potential problem with using questionnaires is that they rely on an underlying theoretical basis, which might differ among researchers, although it has an advantage over objective measures insofar as that results from questionnaires are found to be fairly consistent between different VEs (Regenbrecht, Schubert & Friedmann 1998).

Although presence measurements generally fall under these two categories, it has been suggested that studies regarding presence measurement should make use of measurements under both categories, that is to say, they should make use of quantitative and qualitative measures of presence (Zahorik & Jenison 1998; McCall, O'Neil & Carroll 2004). This points to the possibility that quantitative and qualitative measures might yield differing or even conflicting results (Zahorik & Jenison 1998). The current study's approach to measure presence is discussed in section 3.4.6.3.

2.3.2.4 Effects of presence

One of the motivations for increasing the levels of presence in VR is the fact that it is found to correlate with performance increases (Lombard & Ditton 1997; Regenbrecht, Schubert & Friedmann 1998). Some studies go as far as to list presence as a prerequisite for any performance-driven VR application (Regenbrecht, Schubert & Friedmann 1998; Bystrom, Barfield & Hendrix 1999). It is also found to correlate with similar desirable measures in a training context, such as an increase in skills training, as opposed to simpler media such as handbooks, and higher levels of enjoyment, which can increase motivation (Lombard & Ditton 1997).

Presence can also affect or induce emotional responses, most notably strong emotions, such as fear and anxiety (Diemer et al. 2015). This is often a requirement for certain types of VR applications, such as phobia treatment, since these applications need to provoke similar physiological reactions as their real-world counterparts in order to be effective (Regenbrecht, Schubert & Friedmann 1998). However, Price and Anderson (2007) point out that, although presence is necessary for this sort of treatment, it is in itself not sufficient for phobia treatment (Price & Anderson 2007).

High levels of presence have also been found to influence participant behaviour in the real world after being exposed to VR, such as briefly altering their eating habits (Fox, Bailenson & Binney 2009), and is found to make VR more persuasive as an advertisement medium (Lombard & Ditton 1997). Thus, one might aim to increase the levels of presence in VR to enhance carryover of behaviour from VR to the real world, but one may also choose to decrease the levels of presence to limit this carryover if the behaviour in VR is negative, for example, violent behaviour (Fox, Bailenson & Binney 2009).

As mentioned before, the cause-effect relationship between presence and VR sickness is complicated, since presence is often regarded as playing a role in causing VIMS (Keshavarz et al. 2015). This is because presence is often found to correlate with vection in VEs, which in turn plays a role in VIMS (Lombard & Ditton 1997; Keshavarz et al. 2015). Slater, Usoh and Steed (1995) also suggest that since presence may cause a user to pay more attention to their surrounding (virtual) environment, it may cause a discrepancy between the visual and vestibular system, which might also cause motion sickness (Slater, Usoh & Steed 1995). This complicates the desirability of presence for practical applications since vection is often regarded as a desirable (and sometimes necessary) attribute for VR applications, while motion sickness is an undesirable by-product (Keshavarz et al. 2015). This study's approach surrounding motion sickness is discussed in section 4.2.2.1.

Finally, presence has a causal relationship with believability. Broadly, believability refers to something seeming within the realm of possibility, probability, or credibility and is thus able to be believed as being convincing or true (Cambridge 2018a; Merriam-Webster 2018a; Oxford 2018a). In the current context, believability refers to the ability of VR to convince users that the reality presented is, or can be, from the real world (Magnenat-Thalmann et al. 2005). This can take different forms, such as sensory believability, which refers to the perceived realism of sensory stimuli, and perceptual believability, which refer to the behaviour of virtual agents (Magnenat-Thalmann et al. 2005).

A concept related to believability that has already been discussed is that of an active suspension/suppression of disbelief, during which a participant willingly and temporarily adopts a cooperative mind-set to believe something that seems untrue or impossible (Bates 1992; Steuer 1992; Sheridan 2000), which, as the term suggests, has a positive effect on believability (Magnenat-Thalmann et al. 2005). A willingness to suspend disbelief is highly subjective, as it can vary greatly among individuals as well as across experiences (Lombard & Ditton 1997). While realism is not a requirement for believability, it is expected to have a positive effect, especially with regards to interactivity: if the VE reacts to the user's actions in a way that is expected based on their interactions in the real world, in other words, if the system delivers lawful responses to their actions, this will positively affect the believability of the VR (Zahorik & Jenison 1998; Magnenat-Thalmann et al. 2005). Involvement in the experience is also expected to prevent the user paying attention to cues or aspects that would otherwise have a detrimental effect on their suspension of disbelief (Sheridan 2000).

This section has explored the terms immersion and presence, how they relate to one another and the causes and effects of both. These causes include the use of feedback mechanisms in different sensory modalities, some of which are discussed in the next sections, as well as factors and issues surrounding them.

2.4 Feedback in virtual reality

Since its inception, VR has focused primarily on the visual modality as the primary source of feedback for VEs, with lesser focus given to other modalities such as audio and haptic (Robles-De-La-Torre 2006; Cohen, Villegas & Barfield 2015). Even though visual feedback is sufficient for a variety of applications, such as the simple desktop interface, there is growing incentive for providing a user of VR with a greater variety of high-quality feedback modalities (Robles-De-La-Torre 2006). This section explores the use of feedback mechanisms in VR, specifically audio and haptic feedback since they tend to be neglected in favour of visual

feedback (Robles-De-La-Torre 2006). Thus, the use of audio- and haptic-feedback in VR, as well as the advantages and disadvantages of using each, are discussed.

2.4.1 Audio feedback

The use of audio feedback in computer systems has long served to represent different types of information in computer systems and alleviate the cognitive strain deriving from an overabundance of visually represented information (Blattner, Sumikawa & Greenberg 1989; Gaver 1989). This has led to the creation of a variety of techniques for creating audio for computer applications, such as digital sampling, which involves recording (and thus digitising) real-world sounds and optionally editing them, and digital synthesis, which involves algorithmically modelling soundwaves (Gaver 1993). Using audio feedback effectively for a broad range of applications requires one to address similar issues as one would regarding visual feedback, including (Gaver 1989):

- deciding which types of sounds to use, similar to deciding which types of visual representations to use
- when to use them, similar to deciding when to show specific visual feedback
- how to map user inputs to audio output, similar to deciding how to map user inputs to visual feedback.

It should be noted at this point that the current study focuses on non-voice feedback. One development in audio feedback that is particularly relevant to VR is that of binaural audio, because of its ability to recreate sound seemingly occurring in a 3D environment (Noisternig et al. 2003).

2.4.1.1 Binaural audio

Binaural refers to anything relating to both ears (as opposed to monaural relating to only one ear) (Merriam-Webster 2018b; Oxford 2018b). Binaural audio in the context of VR, also called three-dimensional/holophonic/spatial audio (Seligmann, Mercuri & Edmark 1995; Brown & Duda 1998; Rumsey 2012:1), refers to audio that provides cues in order to be localized in 3D space using one's natural ability to infer this localization by manner of psychoacoustics (Seligmann, Mercuri & Edmark 1995; Brown & Duda 1998; Wanrooij & Opstal 2007).

In our everyday lives, we localise sound on two planes: the horizontal plane, called the azimuth, and the vertical plane, called the elevation (Wanrooij & Opstal 2007). Sound is localised in the azimuth using the difference in arrival times for sound reaching each ear, known as interaural time differences (ITDs) as well as the difference in volume for sound

reaching each ear, known as interaural level differences (ILDs) (Wanrooij & Opstal 2007). Localisation of sound in the elevation relies on what are called head-related transfer functions (HRTFs), which refer to modifications in sound waves caused by diffraction resulting from sound reflecting off our bodies, heads, and outer ears (pinnae) (Brown & Duda 1998; Wanrooij & Opstal 2007). We use the information from HRTFs as well as small unconscious head movements to determine the source of a sound in the elevation as well as to discern between sources coming from in front or behind, since these sources' ITDs and ILDs can be very small (Noisternig et al. 2003; Wanrooij & Opstal 2007). Additionally, we judge the distance of a sound source using many factors, including the volume of sound, the reverberations caused by the environment, and changes in the sound frequency, since higher frequencies attenuate faster over distances (Rumsey 2012:2).

Binaural audio can be digitally modelled by modifying an audio source with these factors (ITDs, ILDs, HRTFs, reverberation, etc.) and thus providing each ear with different audio that provides cues regarding the position of the audio source in 3D-space (Noisternig et al. 2003; Geronazzo, Spagnol & Avanzini 2013). The details regarding the HRTFs, such as the shape of the torso, head, and pinnae, are usually obtained by recording audio with a mannequin with torso, head, and pinnae that correspond more or less to that of a person with microphones located in the "inner ear" of the mannequin, called the Knowles Electronics Mannequin for Acoustic Research (KEMAR) (Harris & Goldstein 1979; Geronazzo, Spagnol & Avanzini 2013). Using a KEMAR has the disadvantage of the HRTFs not being individualised to the user since each person's torso, head, and especially pinnae shapes are unique (Rumsey 2012:2; Geronazzo, Spagnol & Avanzini 2013). In other words, the torso, head, and pinnae of the mannequin do not match those of the listener, which has been found to result in less accurate localisations (Riecke, Feureissen & Rieser 2009; Geronazzo, Spagnol & Avanzini 2013). It is possible to make individualised recordings for each user to match the HRTFs to that of the user, but this is expensive and time-consuming and therefore often impractical (Riecke, Feureissen & Rieser 2009). Another solution to this problem is to use a KEMAR, but to create partial HRTFs (pHRTFs) for each body part separately, allowing one to programmatically modify the parameters, for example, the head-size of the HRTF (Geronazzo, Spagnol & Avanzini 2013).

2.4.1.2 Advantages of audio feedback

Advantages of using audio as a feedback mechanism in a computing environment include the following:

- It provides additional feedback without using up/cluttering precious screen real-estate, allowing more information to be presented (Gaver 1989; Brewster, Wright & Edwards 1993; Palani & Giudice 2014).
- It can be useful when providing visual feedback is impractical or dangerous, for example, if the user has to focus their visual attention on a potentially dangerous task (Fernstrom, Brazil & Bannon 2005).
- It can represent information that is not easily visually representable, for example, to signal the type of input mechanism being used (Monk 1986).
- It can complement visual information so as to enhance it or make it more noticeable (Brewster, Wright & Edwards 1993; Csapó & Wersényi 2013).
- It adds redundancy to information representation which may help users with recall (Brewster, Wright & Edwards 1993; Papadopoulos, Barouti & Koustriava 2016).
- It effectively captures a user's attention, for example, while they are busy with another task (Brewster, Wright & Edwards 1993; Csapó & Wersényi 2013).
- It allows visually impaired users to use the interface (Brewster, Wright & Edwards 1993; Iglesias et al. 2004; Csapó & Wersényi 2013).

Audio has some specific advantages in VR, including:

- It can represent sound in 360° around a user as opposed to the visual channel's limited FOV (Brewster, Wright & Edwards 1993; Xiao & Benko 2016).
- It can provide useful feedback without taking up space in the 3D-environment (Shaw et al. 1993).
- It improves engagement and thus potentially presence (Geronazzo, Spagnol & Avanzini 2013).

Binaural audio's ability to let users localise an audio source increases the "naturalness" of a VE (Rumsey 2012:2), which can be considered to increase the "vividness"-quality of the audio and thus of the entire system (Slater, Usoh & Steed 1995).

2.4.1.3 Disadvantages of audio feedback

Audio feedback also has some disadvantages:

- It has limited use in a loud environment, since the presence of background noise significantly limits the usefulness of audio feedback (Brewster & Brown 2004; Hoggan et al. 2009).
- It can disturb/annoy other people if the feedback is audible by other people (Brewster & Brown 2004).
- It can potentially distract users if audio is presented alongside other feedback (Cheng, Kazman & Robinson 1996).
- Audio feedback is often unsuitable in social situations, due to the feedback requiring the user's full attention (Poupyrev & Maruyama 2003).
- There is a volume cut-off point at which audio feedback stops being useful (Hoggan et al. 2009).
- Blind people prefer not to wear earphones outside, which are often much needed for effective audio feedback, but prevents them from listening to their surrounding environment (Brewster & Brown 2004).

2.4.2 Haptic feedback

Haptic feedback refers to providing feedback in the form of touch, specifically concerning synthesised touch experiences based on computer information (Salisbury & Srinivasan 1997; Berkley, Kim & Hong 2012). Although haptic displays date as far back as the 1940s (Salisbury & Srinivasan 1997), the study and pursuit of haptic devices as an everyday display device was motivated by the development of VR as a natural method of interacting with the (virtual) environment (Berkley, Kim & Hong 2012). This has given rise to a number of haptic feedback display devices, perhaps the most notable early example being the *PHANToM* haptic device by *SensAble* Technologies, which is shown in Figure 20 below (Salisbury & Srinivasan 1997; Berkley, Kim & Hong 2012).

Haptic feedback can be divided into two categories: kinesthetic and cutaneous. Kinesthetic feedback refers to all force feedback that is sensed by the muscles and joints as they interact with an opposing force, while cutaneous feedback refers to all sensations that are sensed through different types of receptors in the skin (Brewster & Brown 2004). Tactile stimuli are divided according to the receptors that respond to various types of stimulation: mechanical stimulation such as vibration is detected by mechanoreceptors, temperature by thermoreceptors, and pain is detected by nociceptors (Necker & Reiner 1980; Kuhtz-Buschbeck et al. 2010).



Figure 20: The PHANTOM device by SensAble Technologies (Salisbury & Srinivasan 1997:1)

Kinesthetic feedback is presented with force feedback devices, such as the *PHANTOM* and the *Dexmo* device by Dexta Robotics (Gomez, Burdea & Langrana 1995; Boland & McGill 2015) which are shown in Figure 21, while cutaneous feedback is presented with the use of tactile devices (Brewster & Brown 2004). These can be divided into two main types:

- vibrotactile devices, such as the *GloveOne* by *Neurodigital* (shown in Figure 22) or *Plexus* by *Plexus Immersive Corp*, that use mechanical actuators that produce vibrations (Antfolk et al. 2013; Hayden 2015; Hayden 2018)
- electrotactile devices that use electrical currents to stimulate nerve endings in the skin to produce touch sensations, such as a “tingle”, itch, vibration, touch, etc. (Sato et al. 2007; Antfolk et al. 2013).



Figure 21: The PHANTOM Desktop (left) can prevent users from pushing forward (Berkley, Kim & Hong 2012:1) while the Dexmo (right) provides individual force-feedback for each finger (Dexta Robotics 2016)



Figure 22: The GloveOne (NeuroDigital Technologies n.d.) uses vibrotactile actuators (right) to create various cutaneous sensations (Hayden 2015)

Karam, Russo and Fels (2009) point out that the human cutaneous (tactile) system as an input channel can potentially be used to convey a lot of information to the user and is a mostly-untapped input channel in modern computing systems (Karam, Russo & Fels 2009). This is supported by van Mensvoort (2002) who points out that computers “engage only a fraction of the human sensory bandwidth” and suggests that haptic-feedback can enrich computer interfaces by making computing interfaces more natural and turning one-way touch-interaction into a two-way interaction with touch feedback from the computer (van Mensvoort 2002). Haptic feedback also differs from audio and visual feedback insofar as that it is inherently bilateral, i.e. we have to interact with the surrounding environment in order for it to provide information about itself, which makes it ideal for gathering information about an environment, albeit real or virtual (Salisbury & Srinivasan 1997).

2.4.2.1 Advantages of haptic feedback

The use of haptic feedback in VR offers several advantages, including:

- an added level of realism, since the overall system feedback comes closer to representing reality (Popescu, Burdea & Bouzit 1999; Blake & Gurocak 2009)
- a more engaging experience, since more of the user’s sensory faculties are engaged (Lucca 2009)
- an added channel of feedback which can be useful in the absence of reliable visual feedback (Popescu, Burdea & Bouzit 1999) or can be used to reduce clutter in the visual modality (Challis & Edwards 2001).

The use of haptic feedback is especially useful when performing telemanipulation, in which an operator remotely controls and interacts with an environment (Niemeyer & Slotine 2004). This is often done with the use of dextrous devices (Turner et al. 1998; Koyama et al. 2002)

and is found to increase the accuracy of task performance and decrease performance times (Meijden & Schijven 2009). Furthermore, we use touch to perform everyday tasks, many of which we do not think about requiring a sense of touch to perform, such as being able to walk, fine motor skills, and communicating through body language (Robles-De-La-Torre 2006). It thus follows logically that the addition of touch in a VE should provide users with the ability to perform many tasks more naturally (Robles-De-La-Torre 2006).

Advantages specific to tactile feedback include (Cheng, Kazman & Robinson 1996):

- not being able to induce muscle fatigue due to their passive nature
- its ability to provide high-depth information due to our fingertips being one of the most sensitive and reactive parts of our bodies
- the fact that tactile feedback devices, such as vibrotactile devices, tend to be cheaper than force-feedback devices.

2.4.2.2 Disadvantages of haptic feedback

Haptic feedback also has some disadvantages:

- Unlike visual feedback, it is not by itself sufficient for most applications and needs to accompany matching visual/audio information to be useful (Wall & Harwin 2001; Yu & Brewster 2002).
- While video and audio are commonplace in a computing environment, devices that provide haptic feedback to the user are often lacking in VR (Robles-De-La-Torre 2006). This is largely due to the price: while vibrotactile and electrotactile devices are relatively affordable, force-feedback devices tend to be quite large and expensive (Berkley, Kim & Hong 2012; Antfolk et al. 2013; Hayden 2015). One reason for this is that force-feedback devices need significantly higher refresh rates than other devices, around 250Hz-300Hz, compared to visual displays requiring around 30Hz, which means that they often require dedicated processing power (Berkley, Kim & Hong 2012).
- It must also be noted that while vibrotactile devices are significantly cheaper than force-feedback devices, they are also associated with longer task-completion times (Antfolk et al. 2013).
- Force-feedback devices also have a limit on the amount of feedback they simulate, since these devices cannot provide an infinite amount of force (Canadas-Quesada & Reyes-Lecuona 2006).
- Haptic feedback is not as intuitive as that from visual feedback, due to technological limitations, and thus requires training by the user (Antfolk et al. 2013). For example,

using nerve stimulation to trigger various haptic sensations still elicits a “foreign feeling” due to the limitations of the technology (Antfolk et al. 2013).

2.4.3 Multimodal feedback

As the discussion in the previous section indicates, the development of VR systems has led to an interest in developing techniques and technologies that engage more of its users’ input and output capabilities (Gomez, Burdea & Langrana 1995; Berkley, Kim & Hong 2012). Apart from being a desirable aspect of immersion, i.e. extensiveness (Slater, Usoh & Steed 1995), the use and interplay of different sensory modalities has since garnered its own attention in research on VR (Hecht & Reiner 2008). Specifically, significant attention is directed towards “intermodal integration”, which concerns itself with how our minds integrate feedback from different sensory modalities (Biocca, Kim & Choi 2001).

2.4.3.1 Intermodal Integration

Traditionally, it has been assumed that our senses work in isolation and that our perception of the world at any given point is merely a summation of what each sense delivers (Russell 1912:3). However, more recent evidence (van Mensvoort 2002; Pérez-Bellido et al. 2015) suggests that everyday perception involves integrating information from different sensory modalities and also involves constantly applying distal attribution to attribute multimodal information to singular objects or occurrences (van Mensvoort 2002; Hartcher-O’Brien & Auvray 2014). Furthermore, stimuli in different modalities originating from a single source might take different amounts of time to reach and be processed by the brain, but are still perceived as originating from the same source, for example clicking on a mouse, which provides visual, audio, and haptic stimuli (Harrar & Harris 2008). This process requires that we group together stimuli that are logically related, such as grouping visual stimuli that are spatially close together, in order to discern different sources of stimuli, which allows us to perceive and understand events or objects in our environment and makes our perception faculties more reliable (Jousmäki & Hari 1998; Bizley, Shinn-Cunningham & Lee 2012).

This integration process, which forms part of our basic perception of the world, is subconscious and is constantly being exercised to construct a stable mental model of the environment (Biocca, Kim & Choi 2001; Bresciani, Dammeier & Ernst 2008; Pérez-Bellido et al. 2015). A possible reason for this interplay between the senses is the convergence of cerebral pathways of different sensory modalities, causing different sensory modalities to affect similar brain areas (Morrot, Brochet & Dubourdiou 2001). The result of this is that our sensory processes are inherently linked, causing us to experience our environment holistically with different modalities contributing differently in different environments and contexts

(Lecuyer et al. 2000; O’Callaghan 2008; Bresciani, Dammeier & Ernst 2008). Lecuyer et al. (2000) refer to this as the “pluralistic nature” of sensory perception.

The processes surrounding intermodal integration are especially relevant in the context of VR since it involves using sensory stimuli, which is often incomplete or contradicting compared to the real world, to make sense of environment (Biocca, Kim & Choi 2001; Biocca et al. 2002). In the case where stimuli are incomplete, which is usually assumed to be the case, since VEs are still far from perfectly replicating reality, users of VR have been known to “fill in” missing information in order to construct stable mental models of the environment, with varying degrees of success (Biocca, Kim & Choi 2001; Hecht, Reiner & Halevy 2006). In the case where stimuli are contradicting, it sometimes occurs that the senses influence each other to the extent that one sense alters perception in another (Jousmäki & Hari 1998; Biocca et al. 2002), which is discussed in detail in section 2.5.

2.4.3.2 Advantages of multimodal feedback

Systems that deliver multimodal feedback have been shown to reduce the reaction time of users, with the number of modalities inversely correlating with reaction times (Hecht & Reiner 2008). Integrating feedback across different modalities is also a requirement for certain types of activities, especially those concerning precise motor functions and hand-eye coordination (Biocca, Kim & Choi 2001). It can also reduce signal-to-noise ratio in interaction by providing high levels of redundancy with the feedback received (Lecuyer et al. 2000; Bresciani, Dammeier & Ernst 2008).

Intermodal integration has also been directly linked with presence since the process of integrating incomplete stimuli is related to the process of constructing a mental model in the presence-process (Biocca, Kim & Choi 2001; Hecht, Reiner & Halevy 2006). Hoggan and Brewster (2006) go as far as to claim that relying on one sensory modality is unnatural since we frequently receive input from multiple sensory modalities in our everyday lives and list an increase in the scope and flexibility of interaction as an advantage of multimodal displays.

2.4.3.3 Disadvantages of multimodal feedback

Presenting the user of VR with information in more than one modality presents the risk of providing conflicting information regarding objects and environments, commonly referred to as intersensory conflict (Biocca & Rolland 1998; Biocca, Kim & Choi 2001). As already discussed in section 2.2.3, intersensory conflict is usually considered to be the cause VR sickness (Biocca 1999; Bos, Bles & Groen 2008).

This section has discussed different feedback mechanisms, advantages, and disadvantages of each, as well as the effects of combining them. As mentioned, the complex interplay between

different sensory stimuli can cause the senses to influence each other in unexpected ways. The next section discusses this phenomenon.

2.5 Intersensory illusions

Illusions have been extensively studied to provide explanations regarding the underlying mechanisms of our perception (Gregory 1968). For example, the Müller-Lyer illusion and the Ponzo figure (see Figure 23) as well as other visual illusions that seem to “fool our eyes” have received much attention in the study of perceptual psychology and biology, among others (Gregory 1968; Lecuyer et al. 2000). One of the reasons why they are studied is because they reveal an important property of our perceptual system: in order for us to observe and understand the world and events around us requires us to not only observe, i.e. collect sensory data, but also to interpret these data against an internal model of how the world works (Gregory 1968). For this reason, it is possible that the brain interprets data incorrectly, causing us to incorrectly observe phenomena (to be “fooled” by our senses), which is the cause for perceptual illusions (Gregory 1968; Lecuyer et al. 2000).

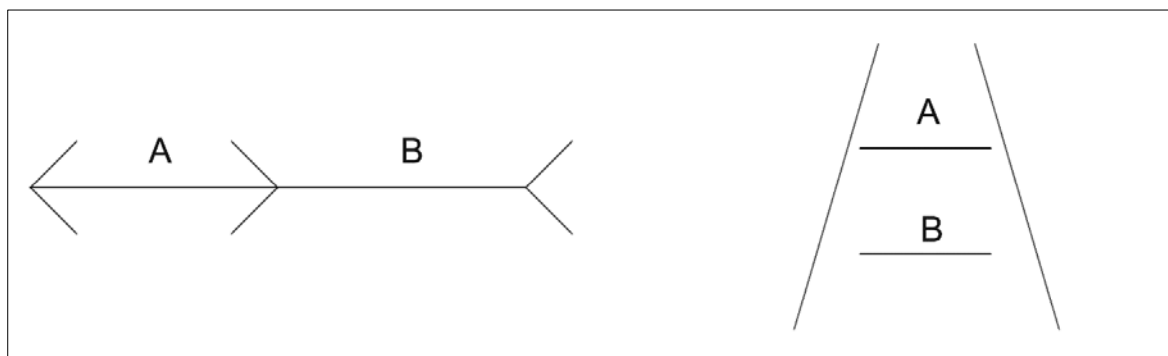


Figure 23: The Muller-Lyer illusion (left) and Ponzo figure (right). In both cases, the lines “A” and “B” are equal in length (Gregory 1968:6,7)

Intersensory illusions (also called cross-modal illusions) are a type perceptual illusion that refer to illusions where stimulation from one sensory modality influences/creates perceived stimulation in another (possibly unstimulated) modality (Biocca, Kim & Choi 2001; Bizley, Shinn-Cunningham & Lee 2012). This might occur as a reaction toward an incomplete set of stimuli, in which case an observer unintentionally “fills in” the missing information with illusory sensory feedback, i.e. perceived feedback in a modality that is not receiving said feedback or might not be receiving any feedback at all (Biocca, Kim & Choi 2001). Although they might appear to reflect incorrect perception by one or more sensory organs, these illusions occur due to a misinterpretation or compensation by our brains in response to specific stimuli (Lecuyer et al. 2000). In other words, they occur because our brains made a mistake, not our senses (Lecuyer et al. 2000).

Intersensory illusions have been known to influence a wide range of senses, including the visual, audio, tactile, proprioceptive, olfactory, and gustatory senses (Shipley 1964; Murray et al. 1999; Morrot, Brochet & Dubourdieu 2001; Hoegg & Alba 2007). The next section discusses some of the most notable examples of intersensory illusions in the literature.

2.5.1 Notable examples

The following examples have been selected as notable examples since, apart from each being stable and robust, they show that the same senses can have a completely different effect or influence in different contexts. For example, in one illusion called the double-flash illusion, audio skews visual perception, while in another called the McGurk effect it is the other way around (Shipley 1964; McGurk & Macdonald 1976). This once again points to a complex interplay between perception in different sensory modalities and during sensory integration.

2.5.1.1 Size-weight illusion

Perhaps the most pervasive and stable example of an intersensory illusion in the literature is the so-called “size-weight illusion”, first demonstrated in 1891. This illusion entails the following: presented with two objects of equal weight but different sizes, a viewer will perceive the smaller object as being heavier (Murray et al. 1999; Heineken & Schulte 2007). Originally meant to demonstrate the influence of skin contact area, this illusion continues to provide compelling evidence of the complex interplay between our senses and internal models (Gregory 1968) and the unexpected effects this interplay can have (Murray et al. 1999). To emphasise this effect, it should be noted that the illusion disappears when viewers close their eyes (Murray et al. 1999; Heineken & Schulte 2007).

Two notable examples regarding the audio modality are the double flash illusion and the McGurk illusion.

2.5.1.2 Double flash illusion

The double flash illusion involves showing a viewer a single visual flash while playing multiple auditory beeps, causing them to “see” multiple visual flashes (Shipley 1964; Shams, Kamitani & Shimojo 2000). Although the earliest studies of this phenomenon did not explicitly use two auditory beeps, the effect has since come to be referred to as the “double flash illusion” (Mishra et al. 2007; Pérez-Bellido et al. 2015). This illusion is also very robust, considering that the effect lasts even when viewers are aware of the illusion (Shams, Kamitani & Shimojo 2000) and persists with many variations of audio and visual properties (Shams, Kamitani & Shimojo 2002; Pérez-Bellido et al. 2015).

2.5.1.3 McGurk illusion

The McGurk illusion involves showing a viewer video footage of a person repeating a syllable while playing audio of a different syllable being repeated, for example, video of a person saying “ga” with audio of them saying “ba”. The result of this is that users report hearing a different syllable, with the results varying based on the video footage, for example, the viewer reports hearing “da” instead of “ba” (McGurk & Macdonald 1976). Like the other examples, the results from this illusion are stable and robust, with users experiencing the effect even though they know they are hearing the wrong syllable (McGurk & Macdonald 1976) and has been studied extensively (Mitchel, Christiansen & Weiss 2014).

2.5.2 Types of intersensory illusions

Biocca, Kim and Choi (2001) list five types of cross-modal sensory interactions in VEs, the following three of which can be considered illusions (Biocca, Kim & Choi 2001):

- **Intersensory biases and adaptations:** occur when conflicting stimuli is presented across multiple sensory channels, such as different visual and audio information. In this case, users often experience a bias toward one of the modalities, for example, the McGurk illusion (McGurk & Macdonald 1976).
- **Cross-modal enhancement or modification:** occur when one sensory channel presents information that alters/enhances perceived stimuli in another channel, i.e. when the senses “talk to each other” (Biocca et al. 2002). For example, an increase in fidelity in one channel may improve perceived fidelity in another channel.
- **Cross-modal transfers or illusions:** occur when stimulation in one sensory channel leads to perceived stimulation in another (unstimulated) channel. This experience is likened to that of synaesthesia where stimulation in one channel produces involuntary stimulation of an atypical nature in another sensory channel (Baron-Cohen et al. 1996; Brang, Williams & Ramachandran 2012).

Biocca, Kim and Choi (2001) also describe a method for creating a cross-modal illusion, which involves creating a representation of a spring in VR which, although it provided no physical force-feedback, created illusory force-feedback using a visual representation of a spring (Biocca, Kim & Choi 2001). This is similar to a study in which illusory force-feedback (in the form of stiffness) was created by altering the visual representation of a moving block (Lecuyer et al. 2000). The author called this phenomenon “pseudo-haptic” feedback, which they later define as “systems providing haptic information generated, augmented or modified, by the influence of another sensory modality” (Lecuyer et al. 2000; Lecuyer et al. 2001).

Although not an illusion, another concept that is related to cross-modal modification is that of cross-modal icons, which refer to abstract icons that can be represented in either the audio or tactile modality (Hoggan & Brewster 2006a). The reason they are significant in this context is that they share properties that can be mapped across different modalities, which means that a user can intuitively map an icon in one modality to its counterpart in another, similar to the notion of the senses “talking to each other” (Hoggan & Brewster 2006a). The properties shared across modalities are discussed in section 2.5.5.

2.5.3 Causes of intersensory illusions

To investigate the underlying causes of intersensory illusions, it is worth first investigating the underlying causes of perceptual illusions (occurring in one sensory modality) and what they reveal about our perceptual system. Consider the Ponzo figure (Figure 23): although lines A and B are equal in length, we tend to see the upper line (A) as being longer than the bottom line (B), even when we know (consciously) that they are equal in length. This can be explained by likening the horizontal lines to a road/railway that leads away from the viewer, in which case line A would have to be longer to be perceived as being the same length as line B from the viewer’s point of view (Gregory 1968). The information from the Ponzo figure is thus compared against depth-perception information from an internal model of the world and adjusted accordingly, which indicates an important underlying cause in many illusions (Gregory 1968). The next section discusses this occurrence in intersensory illusions.

2.5.3.1 Underlying causes of intersensory illusions

Although the precise causes of intersensory illusions have been debated (Lecuyer, Cuquillart & Coiffet 2001), the currently-held belief is that they share a cause above with perceptual illusions, that is, they rely on a previous experience set by an internal model (Gregory 1968; Harrar & Harris 2008; Kilteni et al. 2015). The illusory stimuli are partially influenced by expectation about similar stimuli in the real world (Biocca, Kim & Choi 2001; Kilteni et al. 2015), causing anticipation about the result before it happens (Lecuyer, Cuquillart & Coiffet 2001). The result is that we build up expectation from an internal world-view model, which may alter the experience if it is ambiguous or contradictory (Lecuyer, Cuquillart & Coiffet 2001; Hoegg & Alba 2007).

Another factor that plays a role in these illusions is that of “simultaneity constancy”, which refers to our brain’s attempt to integrate different stimuli seemingly originating from the same source to associate them with that single source, despite differences in timing between them (Harrar & Harris 2008). For example, when one hits a key on a keyboard, it produces visual, aural, and tactile sensations which reach and are processed by the brain at different

times, yet they are still perceived as a single multimodal event (Harrar & Harris 2008). In the case of contradictory information between modalities that are perceived as originating from the same source, our brain's attempt to keep simultaneity and alignment intact may cause it to alter perception in one or more senses (Jousmäki & Hari 1998; Harrar & Harris 2008; Pérez-Bellido et al. 2015). Thus, another underlying mechanism for intersensory illusions requires multimodal stimuli to be perceived as originating from the same object or source (Biocca, Kim & Choi 2001; Heineken & Schulte 2007). This implies a level of correspondence between the different stimuli (Bresciani, Dammeier & Ernst 2008), causing the brain to alter stimuli to maintain the perception of simultaneity (Harrar & Harris 2008; Pérez-Bellido et al. 2015).

2.5.3.2 Factors that influence intersensory illusions

With regards to the simultaneity constancy mentioned, the extent to which our brains integrate multimodal stimuli can be adapted to different situations, based on factors such as previous experience and whether the stimuli occurs repeatedly (Harrar & Harris 2008). In other words, if stimuli in two or more modalities occur repeatedly, the “window of acceptance” (i.e. the threshold of perceived simultaneity) is increased (Harrar & Harris 2008). In VR, a factor found to influence the simultaneity between senses, as well as the overall illusion, is immersion, since it increases the compellingness of the experience, causing users to associate real stimuli with virtual stimuli more easily (Heineken & Schulte 2007). It has also been found that two modalities that share properties are more easily integrated, meaning that a user will perceive simultaneity between them more easily (Hoggan & Brewster 2006a).

With regards to the interplay between stimuli, using more than one modality to influence another is not only found to exercise greater intersensory influence on the modality being influenced, but evidence suggests that the influence from both modalities together is greater than the sum of the influence from either modality by itself (Bresciani, Dammeier & Ernst 2008). It must also be noted that, in the context of generating illusory haptic feedback, the user's actions also play a direct role, for example, if a user is asked to manipulate a joystick or perform gestures, their actions induce some degree of haptic and proprioceptive feedback (Lecuyer, Cuquillart & Coiffet 2001). Therefore, their illusory haptic feedback would also be influenced by the side effects of performing motor tasks in the real environment, which means that the illusion will be influenced by user-specific and context-specific factors as well (Lecuyer, Cuquillart & Coiffet 2001).

2.5.3.3 Direction of cross-modal interactions

As the examples in section 2.5.1 illustrate, the influence of one sense over another, i.e. the direction of the cross-modal interaction, varies across illusions. Some explanations have been

given for this, such as the “modality appropriateness” hypothesis, which dictates that whichever modality is most suited for a specific task will carry the most influence in intersensory conflicts (Shams, Kamitani & Shimojo 2002; Bresciani, Dammeier & Ernst 2008). For example, vision is said to dominate in spatial tasks, while audition is said to dominate in temporal tasks (Shams, Kamitani & Shimojo 2002; Bresciani, Dammeier & Ernst 2008). This theory, however, is debated since the direction of interactions are also found to depend on the characteristics or parameters of the stimuli (Shams, Kamitani & Shimojo 2000; Shams, Kamitani & Shimojo 2002). Another explanation is that our brains choose the least variable or uncertain modality depending on the situation as well the stimuli and that this stimuli then has the most influence over other stimuli (Bresciani, Dammeier & Ernst 2008). For example, if users are better at discerning the number of audio beeps than they are at discerning the number of visual flashes, then audio perception is more likely to influence visual perception (Bresciani, Dammeier & Ernst 2008).

Biocca, Kim and Choi (2001) found that using the visual analogue of a haptic force (in their case, a virtual spring) helped increase illusory force feedback. This is similar to a finding by Lecuyer, Cuquillart and Coiffet (2001) that correlated the amount of visual distortion or deformation applied to a virtual object with an increase in illusory force feedback, but also listed the user’s cognitive strategy as influencing the results. A study by Morrot, Brochet and Dubourdieu (2001), which involved altering the perceived odour of wine by changing the colour, found that the cognitive component, in this case the colour, dominated over the sensory component, the odour, thus altering the way that the sensory component was being processed cognitively (Morrot, Brochet & Dubourdieu 2001). It is also possible that no sensory modality dominates in the case of contradictory stimuli, in which case it is suspected that the user’s perception of the dominant stimuli would oscillate between the ones being presented (McGurk & Macdonald 1976).

2.5.4 Usefulness of intersensory illusions

To understand why intersensory illusions are useful and worth studying, consider another illusion called the “ventriloquism effect”: when hearing a sound, we tend to localise the sound as coming from a source that is synchronised with the sound (Hershey & Movellan 2000). For example, when we watch television we tend to localise the sound as coming from the mouths of the actors rather than from the television speakers (Hershey & Movellan 2000). Although the technologies regarding the experience are limited (no matter where the sound sources are on screen, the sound will always emanate from the television speakers), the ventriloquism effect causes viewers to automatically synchronise the audio with its apparent source in the

video (Biocca, Kim & Choi 2001). Thus, they overlook the technological limitations of the medium, which enhances the experience (Biocca, Kim & Choi 2001).

As mentioned before, VR systems are limited in the sensory feedback they can provide users, especially with regards to haptic feedback (Robles-De-La-Torre 2006). Intersensory illusions can thus be used to provide limited VR systems with pseudo-haptic feedback to enhance the experience of the VE (Biocca, Kim & Choi 2001; Biocca et al. 2002) as an alternative to recreating haptic experiences from the real world (Lecuyer, Cuquillart & Coiffet 2001). By investigating and understanding the influence that the senses can have on each other, one can use this knowledge to provide VR systems with a wider range of interactions and feedback possible (Srinivasan, Beauregard & Brock 1996; Wu, Basdogan & Srinivasan 1999). Thus, one can enhance the interaction a user can have with the VE by “augmenting” the displays (DiFranco & Beauregard 1997).

The use of illusions is especially relevant in the context of VR, since integral VR concepts, such as presence, are based on illusions (Lombard & Ditton 1997). To become “part” of a VE thus also involves an illusion as the user constructs a mental model of the environment based on synthesised data and integrates these data to infer couplings between user actions and environment outcomes (Biocca, Kim & Choi 2001). Lecuyer et al. (2000) stress this point in their claim: “Illusion plays a central role in VE perception”. Intersensory illusions in VR have also been directly linked with presence, possibly due to sharing the underlying mechanism of constructing a mental model during intermodal integration (Biocca, Kim & Choi 2001; Biocca et al. 2002; Heineken & Schulte 2007).

2.5.5 Audio and tactile mapping

This section investigates the connection between the audio and tactile modalities as well as ways of mapping stimuli from one to the other.

2.5.5.1 The relationship between audio and tactile

While there have been studies involving intersensory illusions between audio and haptic sensations (Jousmäki & Hari 1998; Canadas-Quesada & Reyes-Lecuona 2006), the research on the matter is largely dominated by research involving the visual modality (Eitan & Rothschild 2011) and as such, the relationship between audio and tactile perception is still largely unclear (Crommett, Pérez-Bellido & Yau 2017). For example, the size-weight illusion, double-flash illusion, McGurk effect, and ventriloquism effect, all notable and well-documented illusions, all focus on the visual modality (Shipley 1964; McGurk & Macdonald 1976; Murray et al. 1999; Hershey & Movellan 2000). This is largely due to the notion that the

visual modality is often found to be the dominant modality in intersensory interactions, a phenomenon known as “visual capture” (Biocca et al. 2002).

However, on a perceptual level audio and tactile experiences are very similar, due to them both relying on pressure and vibration stimuli and thus making use of properties such as amplitude and frequency (Eitan & Rothschild 2011). When interacting with objects, we thus encounter similar audio and tactile properties originating from the same sources, with the very same vibrations being interpreted as touch also reaching our ears (Eitan & Rothschild 2011). Furthermore, they both share a temporal property that might enhance the perception of simultaneity between them (Hoggan & Brewster 2006a), which might also be the source of supposed supramodal mechanisms that perform canonical computations on various perceptive qualities, such as temporal frequency, rate, motion, etc., regardless of input modality (Crommett, Pérez-Bellido & Yau 2017).

2.5.5.2 The mapping between audio and tactile

In a set of related studies, four properties were identified that can be intuitively mapped between audio and tactile feedback (Hoggan & Brewster 2006a; Hoggan & Brewster 2006b; Hoggan & Brewster 2007):

- **rhythm:** by altering the rate of audio beats and vibrotactile pulses (as discussed in section 2.4.2)
- **roughness:** by altering the audio timbre (such as choosing different instrument sounds) and modulating the vibrotactile amplitude
- **intensity:** by altering the amplitudes of audio and vibrotactile feedback
- **spatial location:** by altering the spatial audio’s perceived location and using different vibrotactile devices located in different areas of the user’s body (such as their wrist or waist).

It was found that users could accurately map feedback that is encoded in the audio and tactile modality with these four properties between modalities without training in either modality (Hoggan & Brewster 2007).

Stemming from the vocabulary usually used to describe musical sounds, Eitan and Rothschild (2011) asked participants to align audio properties with the following tactile properties: pitch, loudness, timbre, and vibrato (Eitan & Rothschild 2011). The following associations were found to be significant (Eitan & Rothschild 2011):

- **Pitch:** higher pitch height was associated with sharper, rougher, harder, lighter, colder, and drier tactile sensations.

- **Amplitude:** louder sound was associated with sharper, rougher, harder, heavier, and colder tactile sensations.
- **Timbre:** the timbre of a violin was more associated with blunter, rougher, harder, colder, and drier tactile textures, compared to a flute.
- **Vibrato:** sounds with vibrato were associated with lighter, warmer, and wetter tactile sensations.

Some of these associations can be explained by the physical properties of the sound waves that produce them (Eitan & Rothschild 2011):

- A sound with a higher pitch has shorter waveforms than a lower pitch sound, making it jagged and thus sharper.
- Louder sounds cause greater pressure difference in the air, which exercises more physical force on our ear receptors, similar to how heavier objects exercise greater pressure on our skin receptors.

In a similar study by Tajadura-Jiménez et al (2014), participants stroked their finger across a wooden surface, while audio was played to them. Granular synthesis was used to produce sounds using two different source sounds (a “grainy” surface and a “smooth” surface) and the mean high frequency of the audio grains was altered in different testing conditions. An increase in frequency was found to have different effects on the perceived tactile qualities of the grains originating from different source sounds (Tajadura-Jiménez et al. 2014):

- For the “grainier” sounds, an increase in frequency made the surface feel colder.
- For the “smooth” sounds, an increase in frequency made the surface feel more paper-like.

The results of these studies suggests that exploiting the physical properties shared between audio and tactile can be used to create stronger cross-modal mapping between them.

Another strategy one might adopt for cross-modal mapping is to rely on the user’s internal model to create audio analogies of tactile sensations, similar to the strategy employed by Biocca, Kim and Choi (2001) to create a visual analogy of force-feedback, in their case a virtual spring. By using audio cues that a user might readily associate with certain information in another sense, the cues might be intuitively interpreted cross-modally (DiFranco & Beauregard 1997), thus enforcing the perception of simultaneity.

The next section discusses an audio effect that has the potential to enhance the cross-modal capabilities of audio feedback.

2.5.5.3 Proximity effect

Due to the design of directional microphones, the sound that is transmitted from a source that is very close to the microphone, i.e. that is in the “near field”, often causes an increased amplitude in the lower frequencies, which is generally referred to as the proximity effect (Josephson 1999; Neumann 2018). Although the technical details regarding the exact causes of this effect are outside the scope of the current study, the details regarding the frequency boost caused by the proximity effect is potentially useful, since the perceived proximity of virtual objects can potentially enhance the cross-modal capability of audio feedback by “internalising” the perceived source of the audio and give the audio source a perceived “intimacy” (Brungart 2002; Phillips 2015). Due to the manufacturing differences between microphones, the frequencies at which amplitude is boosted due to the proximity effect differs between microphones, but generally ranges between 135Hz and 500Hz (Brungart 2002; Schneider 2010; Clifford & Reiss 2011; Neumann 2018), an example of which is indicated in Figure 24 below.

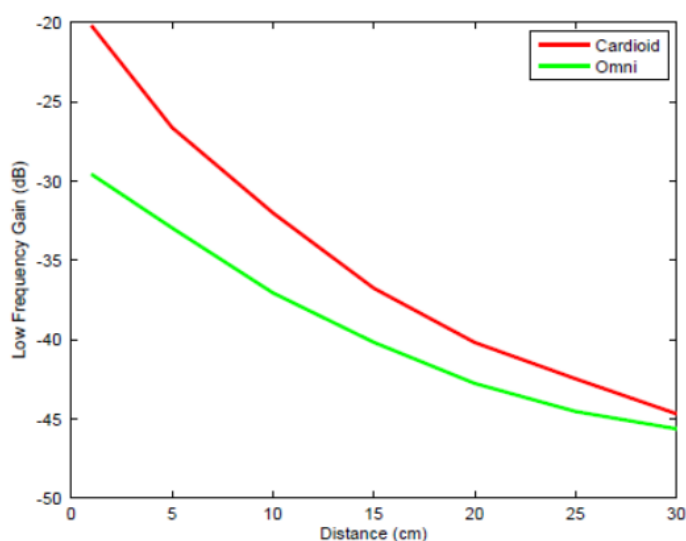


Figure 24: An example of low frequency response for two different microphones (cardioid- and omni-microphones) across small distances (Clifford & Reiss 2011).

2.6 Summary

In this chapter the concept of virtual reality, as well as related concepts, were discussed along with the usefulness of VR in real-world situations, the advantages it provides, and the potential pitfalls. The concepts of immersion and presence, their importance, and how to achieve both were then discussed, which included motivation for the use of multiple feedback modalities in VR. A brief investigation into different feedback modalities revealed that, while the visual modality is often explored in VR research, the audio and haptic modalities are

explored less, and the haptic modality is not utilised to its full potential, due to drawbacks such as cost and technological limitations. An investigation into intersensory illusions revealed that sensory information from one sensory channel can alter/create sensory information in another, possibly unstimulated channel. The possibility of using this illusion to make up for the lack of haptic stimuli with audio stimuli was then explored by investigating similarities between audio and haptic feedback as well as strategies to map information from the one sense to the other. This chapter also revealed a lack of methods for using intersensory illusions between the audio and tactile modalities to make up for the lack of tactile feedback in VR systems. The next chapter thus discusses the methodology for investigating audio feedback as a viable medium for inducing illusory haptic feedback, specifically regarding the design of experiments that test this viability and the gathering of data to support or refute this claim.

3. Chapter 3 - Methodology

This chapter starts with a discussion of the chosen research paradigm and the accompanying research methodology chosen for the current research.

An interpretivist paradigm considers reality to be a construct of an individual and therefore does not assume one shared reality, but rather a set of realities tied to individuals that are shaped by their experience and context (Pickard 2013:1). As such, the act of researching will inevitably have an effect on a research subject and thus on the results obtained from said subject, which is then further influenced by the researcher themselves through their own constructed reality manifested through tacit knowledge and/or biases (Pickard 2013:1).

Methodologies, the approaches to conducting research to investigate problems, phenomena, etc. (Taylor, Bogdan & DeVault 2015:1), can generally be divided into either quantitative and qualitative research (Roberts 2010:12). Quantitative methodologies belong to a positivist paradigm, which assumes a universal, shared reality which can be objectively observed in order to find solutions to problems, including social problems (Pickard 2013:1). Quantitative methodologies therefore rely on identifying the variables that determine the outcome of experimental research as well as investigating the effect of changing those variables (Roberts 2010:2; Pickard 2013:1). The results from quantitative research therefore often takes the form of numerical data with the aim of being generalized to wider contexts and groups (Roberts 2010:2; Pickard 2013:1).

Qualitative methodologies, on the other hand, belong to an interpretivist paradigm which rejects the notion that human and social factors can be studied in a similar objective way as natural laws, such as physics (Pickard 2013:1; Corbin & Strauss 2014:2). Because of this emphasis on the subjective over the objective, regarding human and social factors, qualitative methodologies produce descriptive data that focus on experiences and perspectives (Taylor, Bogdan & DeVault 2015:1). Qualitative research also embraces the role the researcher plays in the final results, thus including the researcher as a research instrument who then uses their own tacit knowledge and experience to guide the research and interpret the results (Pickard 2013:1; Corbin & Strauss 2014:1). The research produced using a qualitative methodology is also presented in context, thus trading the goal of generalizability for transferability due to the highly individualized nature of human experiences (Pickard 2013:1).

3.1 Research methodology

The experience of “entering” VR, as discussed in section 2.3.2.1, is inherently linked to the concept of presence (Steuer 1992), which makes it highly subjective and individualized (Slater

& Wilbur 1997). This is partially due to the highly subjective factors that play a role in causing presence, as discussed in section 2.3.2.2, such as through “lawful” responses (Zahorik & Jenison 1998) and social interactions in VR (Nowak & Biocca 2003), and is also greatly affected by mental and physical characteristics of the users themselves (Biocca 1999; Fox, Bailenson & Binney 2009). As such, when discussing or investigating experiential qualities of a VR system, it would be most appropriate to adopt a qualitative methodology to study the behaviours and reactions of users of VR systems, since qualitative methodologies place emphasis on descriptive data that are produced in social settings, which is therefore more appropriate for exploring mental states and experiences (Corbin & Strauss 2014:1; Taylor, Bogdan & DeVault 2015:1).

This also holds true for the nature of the topic under investigation: intersensory illusions. Since the origin of illusions are psychological rather than physiological, i.e. “mistakes made by the brain, not the senses” (Lecuyer et al. 2000), their occurrence lies at the core of subjectivity. Additionally, the current study’s focus on user “experience”, i.e. their experience resulting from various sensory channels of input as well as the integration that occurs (Pérez-Bellido et al. 2015) further points toward a qualitative methodology with its capacity for dealing with the inner states and behaviour of people in various contexts (Corbin & Strauss 2014:1; Taylor, Bogdan & DeVault 2015:1). The capacity for qualitative research to be flexible with regards to how studies are carried out is also useful for dealing with unpredictable factors relating to human experience and testing (Pickard 2013:1; Corbin & Strauss 2014:1).

3.1.1 Value of the research

In quantitative research the value of research findings is usually judged by the rigour in conducting research and its ability to be generalised to a broad context of environments and populations (Pickard 2013:1; Corbin & Strauss 2014:4). The current research, however, with its focus on a qualitative approach rejects the notion that findings resulting from studying human and social factors can have the same rigour as the study of, for example, natural phenomena, thus eliminating the possibility of generalizability in the quantitative sense (Morgan, Krueger & King 1998:6; Pickard 2013:1). Instead, emphasis is placed on the trust that the results obtained do, in fact, stem from the data in a way that is useful, which can be judged by adherence to the techniques and protocols of the research and data collection methods used (Morgan, Krueger & King 1998:6), the transferability of larger theoretical concepts across various similar contexts (Morgan, Krueger & King 1998:6; Pickard 2013:1), and the extent to which findings can be traced back to the raw data generated by the research (Pickard 2013:1).

These criteria for valuable research findings thus rely on proper use of methods, especially that of analysis of raw data to reach conclusions. Before these methods are discussed, however, the process for developing the required software is discussed next.

3.2 Software process model

All software development follows some sort of software process model, whether intentionally or unintentionally (Royce 1987). In simple terms, the software process model is an abstract representation of all the steps/activities and requirements at each step, as well the order of these steps when developing software (Boehm 1988; Sommerville 1996; Munassar & Govardhan 2010), which is why even the simplest and most general processes of developing software can be defined as using a software process model (Royce 1987; Boehm 1988). The purpose of intentionally using a predefined model is to avoid some of the problems that may arise as a result of the misapplication of the steps involved as well the order of those steps (Boehm 1988). However, this does not mean that there is a single “correct” process model that applies to all applications of software development; the ideal process model still depends on the problem, developer(s), type of application, etc. (Sommerville 1996). Software process models differ from development methodologies in that the former establish the steps that are taken in the project’s development lifecycle, the order of these steps, and the criteria for progressing between steps, while the latter focuses on the details of each step and what deliverables are created from each (Boehm 1988). Development methodologies can thus be thought of as more concrete implementations of more abstract process models (Boehm 1988).

The current research made use of the modified waterfall approach, which is similar to the “pure” waterfall model, but allows for alternating between subsequent steps in the process (Royce 1987) as illustrated in Figure 25. The reason for this is that the requirements of the development project were drawn from the literature, which enforced a linearity between design and development, thus requiring a process model that emphasises initial planning and design over continuous feedback (Royce 1987; Munassar & Govardhan 2010). Additionally, the known problem of stakeholders not being able to articulate their requirements at the planning phase of the project, which is a notable disadvantage of the waterfall model (Sommerville 1996), were not present in the current context, as these were drawn from the literature by the researcher. However, a degree of flexibility was still needed between implementing and testing, as user needs still be needed to be taken into account, thus making the modified waterfall more appropriate than the pure waterfall, which enforces linear progression between subsequent project phases (Royce 1987).

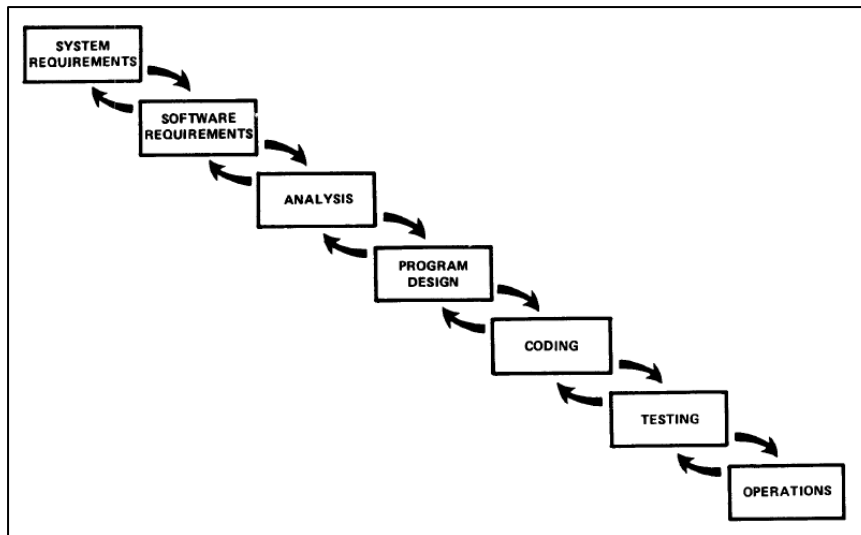


Figure 25: Waterfall model allowing for interactivity between adjacent steps (Royce 1987:3)

With the process model for developing the software for the experiment having been established, the method for conducting the research can now be defined.

3.3 Research method

The aforementioned focus on the user's (subjective) experience with the VR system points toward a research method that requires the capturing and interpretation of user-experience data, i.e. data that result from a user's experience with a system, possibly while trying to complete some sort of task or meet some goal while using the system (Barnum 2010:1). The most appropriate research method, therefore, was usability testing, which involves giving users a set of meaningful tasks and gathering data about their performances and experiences through observation and interaction (Barnum 2010:1; Pickard 2013:11).

These data are then analysed in order to learn more about the system itself, ideally, regardless of the user(s) involved, all of which takes place in a structured context (Barnum 2010:1; Pickard 2013:11). This took place in a controlled lab setting, in order to eliminate as many unwanted variables as possible (Preece, Sharp & Rogers 2015:14). However, as is often done along with usability tests (Barnum 2010:3, 6), the current study included a smaller method, in the form of a pilot usability test, that preceded the main usability test.

3.3.1 Pilot usability test

A preliminary method prior to the main usability test was to conduct a pilot test of the final usability test. The pilot test in this case refers to a usability test with a small number of users, not to collect and analyse data, but to finalise the details of the test itself in order to solve any

logistical and/or other problems that might cause problems during the actual test (Barnum 2010:6; Preece, Sharp & Rogers 2015:7). It thus took place with the same experimental content and procedures and with the same data collection methods as the final test (Barnum 2010:6; Preece, Sharp & Rogers 2015:7). Furthermore, the pilot test employed users with expert knowledge of academic research and testing in order to gather more detailed feedback regarding the test setup and data collection measures.

The pilot test therefore took place during development to identify and correct problems, both with the system and with the testing procedures themselves; the test can therefore be classified as a summative test (Rubin & Chisnell 2008:3). It also allowed for validating the effectiveness and amount of content generated from the data collection methods to validate the effectiveness of the testing procedure (Barnum 2010:6; Preece, Sharp & Rogers 2015:7). Since the results of the pilot test were used to improve the systems or procedures for the final test, the data were not analysed nor used in the final results. (The results of the pilot study and how they are used are discussed in section 5.1.) The details of the pilot study were therefore similar to that of the main usability test, discussed in section 3.3.2 below, albeit with a much smaller number of participants. It should be noted at this point that the main usability test is referred to simply as the “usability test” in the current study and that, when referring to the pilot usability test instead, the term “pilot usability test” or “pilot study” is used.

3.3.2 Main usability test

The term usability test refers to a range of possible procedures, ranging from formal to informal, to study the behaviour of a set of users while interacting with a system, completing a series of tasks to try and accomplish one or more goals (Rubin & Chisnell 2008:2; Barnum 2010:1; Preece, Sharp & Rogers 2015:14). This involves a person or group of people, known as moderators, collecting data through different means, such as observation and interviews, in a controlled setting and often involves a degree of experimental or quasi-experimental procedure to study the effects of different interfaces on user behaviour (Rubin & Chisnell 2008:2; Pickard 2013:11).

The data collected from usability tests can be divided into two categories (Rubin & Chisnell 2008:8; Barnum 2010:5):

- **Performance data:** these data are the result of user behaviour and measures their use of the system/interface against some sort of metric or benchmark, such as measuring their task completion time, how many errors they made, etc.

- **Preference data:** these subjective data are obtained directly from users by gathering their opinions or feelings about a system/interface, for example, by finding out how easy/difficult they found the interface to use.

Although one might be inclined to associate performance data with quantitative measures and preference data with qualitative measures, both categories can deliver either quantitative or qualitative data (Rubin & Chisnell 2008:8). For example, qualitative performance data can come from users pointing out parts of a system that they have difficulty understanding (Rubin & Chisnell 2008:8) and quantitative preference data can result from users rating perceived difficulty by means of a system using a numerical scale (Barnum 2010:5). Since the focus of the current study was to collect rich experience-data from users, the focus of the usability test was on collecting qualitative preference data.

To understand the role of the usability test and its relevance for this study, two important concepts are first elaborated on: usability and user experience.

3.3.2.1 Usability and user experience

There are many different views of usability in the context of interfaces. One approach is to approach usability in a pragmatic way, which assesses how well and how easily an interface allows a user to accomplish a goal, not drawing attention to itself, but rather being “invisible” (Rubin & Chisnell 2008:1).

Rubin and Chisnell (2008) list the following attributes which measure a product’s usability (Rubin & Chisnell 2008:1):

- **Usefulness:** this refers to the extent to which a product allows users to accomplish a goal, thus making it useful. If a product’s functionality is unwanted or is outmatched by that of another product/process, a user simply won’t use it, which invalidates any further investigation into usability.
- **Efficiency:** this attribute measures the time it takes for a user to accomplish their goals.
- **Effectiveness:** this refers to the extent to which the product’s behaviour aligns with the user’s expectations and thus how easily they can use it to accomplish their goals. This attribute is usually inversely correlated with error-rate.
- **Learnability:** given a set period of time, this attribute refers to how well the user can learn to use the system competently.
- **Satisfaction:** this attribute captures the way the user feels about a product, which is likely to reflect positively on their performance using the product.

The authors also include “accessibility” as a measurement for the extent to which people with disabilities can use the system (Rubin & Chisnell 2008:1), however, including people with disabilities as a user group is outside the scope of this study.

Perhaps the best-known and most used definition of usability, at the time of writing (Barnum 2010:1; Bevan, Carter & Harker 2015), is the one drawn up by the ISO (International Standards Organisation) in their ISO 9241-11:1998 standard, where usability is defined as: “Extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use” (ISO/IEC 1998).

This definition is accompanied by the following definitions (ISO/IEC 1998):

- **Effectiveness:** accuracy and completeness with which users achieve specified goals
- **Efficiency:** resources expended in relation to the accuracy and completeness with which users achieve goals
- **Satisfaction:** freedom from discomfort, and positive attitudes towards the use of the product
- **Context of use:** users, tasks, equipment (hardware, software and materials), and the physical and social environments in which a product is used
- **User:** person who interacts with the product
- **Goal:** intended outcome”

Both of these definitions and accompanying concepts focus on goal-oriented systems and place less focus on user-experience (Rubin & Chisnell 2008:1; Barnum 2010:1). This has led to criticism, as some argue that users come to expect usable interfaces by default and that there should be more focus on the user’s experience of the product (Barnum 2010:1; Bevan, Carter & Harker 2015). Bevan, Carter and Harker (2015) point out a number of shortcomings in the current ISO 9241-11:1998 standard, including the following:

- the perception of usability as a “hygiene factor”, dealing only with the extent to which an interface allows users to accomplish their goals, but not with their overall experience (positive/negative) in using the interface. The authors believe that more emphasis should be place on including aspects of user experience in the “satisfaction” definition.
- the fact that usability can be evaluated in more ways than simply through effectiveness, efficiency and satisfaction
- its lack of addressing possible negative outcomes that could arise as a direct result of inadequately implemented usability.

However, as pointed out in (Bevan, Carter & Harker 2015), there is a separate ISO standard for user experience, namely ISO 9241-210:2010, defined as: “Person's perceptions and responses resulting from the use and/or anticipated use of a product, system or service” (ISO/IEC 2010). Thus, for the purposes of this study, usability and user experience are considered as separate concepts, although the study regards the user's (positive or negative) perception toward the system as being an important result of their interaction with the system as it is likely to influence the results of their use of the system (Rubin & Chisnell 2008:1).

Due to the range of motivations and outcomes of a usability test, there are many different types of tests, classified according to many different aspects of the tests themselves.

3.3.2.2 Types of usability test

There are different ways of distinguishing types of usability tests from one another, with regards to several aspects such as when the test takes place in the development cycle (Rubin & Chisnell 2008:3; Barnum 2010:1) as well as the structure and purpose of the test itself (Rubin & Chisnell 2008:3; Barnum 2010:5). With regards to where the test took place in the development lifecycle, the current research made use of validation testing, which is used late in the development cycle (usually close to the end) to measure the system against some benchmark for performance to ensure that the system meets the standards and requirements set out for it (Rubin & Chisnell 2008:3; Barnum 2010:1). Validation testing usually produce quantitative (performance) data, but can also collect qualitative data when explaining reasons for substandard performance (Rubin & Chisnell 2008:3).

A validation test was chosen as the main purpose of the test was to measure the effectiveness of the implementation of interactions that create intersensory illusions. Therefore, it could only be conducted when the system had been completed and was used to measure the system's success in accomplishing its goal (Rubin & Chisnell 2008:3; Barnum 2010:1). However, unlike most validation tests, the usability test of the current study produced mainly qualitative data, the reason for which has been discussed in section 3.1. In this regard, the usability test differed from the typical consumer-oriented tests (Schumacher & Lowry 2010) due to the focus of the test moving away from a fixed goal-oriented view that is usually measured by performance metrics, towards an experience-driven view that cannot be captured and understood in a purely quantitative way (Barnum 2010:4; Pickard 2013:1).

With regards to how the test was structured, the current research made use of a comparative test, which presents participants with two or more “designs” and collects data about their preferences (Rubin & Chisnell 2008:3; Barnum 2010:5). The “designs”, for the purposes of the current research, were different technological implementations, each of which represented

different attempts to invoke intersensory illusions. Although comparative testing may make use of performance data when comparing products/interfaces, the current research used it in an observational capacity to produce qualitative data on user preferences (Rubin & Chisnell 2008:3). The test thus focused on collecting user-preference data as well as further qualitative data to elaborate on participants' choices of implementation and thus of experience in an attempt to understand how the aspects of the different implementations affected the participants' perception of the virtual stimuli.

The use of comparative testing introduced two questions to be addressed: how would participants be assigned to testing different interfaces and how would scenarios/tasks be distributed between participants (Barnum 2010:5; Preece, Sharp & Rogers 2015:14). With regards to the first question, a within-subjects design was used, which involved letting all users test all interfaces (Barnum 2010:5). Advantages of this design include the fact that the possibility of skewing of results by individualised experience/expertise is lessened (Preece, Sharp & Rogers 2015:14) and less users are needed to perform the test (Barnum 2010:5). A disadvantage of a within-subjects design is that testing takes more time as opposed to other methods which divide designs or interfaces between participants, thus only letting some participants test some interfaces (Barnum 2010:5; Preece, Sharp & Rogers 2015:14).

Nevertheless, within-subject design was used, since part of the aim of the test was to collect preference data, more of which could be collected by exposing participants to more test conditions. With regards to the number of users being tested at a time, the test only involved one participant at a time to avoid the additional variables introduced by letting participants test in pairs or groups, i.e. pair-wise testing (Preece, Sharp & Rogers 2015:14), and also due to the data collection methods that were used, which are discussed in section 3.4.

With regards to the second question, the current study let participants finish all the tasks in sequence, moving on to the next once they completed each task, without the intervention of the moderator (Barnum 2010:5). Two advantages of this approach are that the testing is efficient, since the participant can quickly progress between tasks and that the participant is not interrupted, which is useful if the tasks are sequentially linked (Barnum 2010:5). Thus, all tasks were given to the participant to complete in sequence and data were collected afterwards. The reason for this is that interrupting the user during testing was expected to have an adverse effect on the system being "inclusive" as a factor of immersion (Slater & Wilbur 1997), which would have an adverse effect on presence (Slater 2003).

3.3.2.3 Details of the usability test

With the usability test classified according to its place in the development cycle, how it was structured, how participants were assigned to testing different systems/interfaces, and how tasks were distributed to users, the test can be further described by defining the details that determined how the test took place, who was be tested, etc. For the current section, the following details are addressed (Rubin & Chisnell 2008:5; Barnum 2010:5):

1. The goals of the usability test
2. The subgroup of users that were tested
3. How the system was tested
4. The logistic details of the test
5. The role that the moderator (or in this case, the researcher) played

It should be noted that four points listed by Rubin & Chisnell (2008:5) have been omitted from this list: the research questions to be answered, the list of tasks for testing, which (qualitative and/or quantitative) data were collected, and the reporting of contents and presentation. The reason for this is that the research questions, task list, and data collection are addressed in sections 1.5, 4.2.2.6, and 3.4 respectively and the format of writing a findings-report is predetermined by the nature of this study, which makes discussion of these factors irrelevant at this point.

3.3.2.3.1 Goals of the usability test

The main goal of the usability test, which was also the reason for doing a usability test in particular, was to determine the effectiveness of the implementations of interactions that aimed to produce intersensory illusions. However, by collecting rich qualitative data, the aim was also to analyse these data to provide insight into the details of multimodal perception in VR. This insight could then be used to design more immersive multimodal interfaces in VR.

3.3.2.3.2 Subgroup of users that were tested

The first issue regarding the subgroup that was tested is the size of the subgroup that was tested. Idealistically, there is no drawback to using as many users as possible during testing (Rubin & Chisnell 2008:5), which means that the number is constrained mainly by limited time and resources (Rubin & Chisnell 2008:5; Barnum 2010:5). However, it has been suggested that the benefits of using more users, i.e. an increase in the number of errors found in an interface, encounters progressively diminishing returns as the number of testing participants increases (Nielsen 1994; Nielsen 2012).

Nielsen (1994a, 2012) suggests that the optimal number of testing users, regardless of interface or platform being tested, is five users, a number which has been widely agreed with

(Rubin & Chisnell 2008:5; Barnum 2010:5). However, there are a few exceptions, such as quantitative studies (aiming for statistical significance), card sorting, or eye tracking tests (Nielsen 1994; Nielsen 2012). The argument against simply using as many test participants as possible is that each additional user's error detection results overlap significantly with that of all other users, resulting in a notable decline on return on investment for additional users, starting at two users (Nielsen 1994; Nielsen 2000). However, since the current study focuses on user experience rather than error detection, the point of diminishing returns is assumed to be higher.

Nielsen goes on to suggest that a more appropriate strategy would be to lessen this overlap by choosing testing participants with different backgrounds relating to the domain area, such as previous computer experience (Nielsen 1994). Given values obtained from large numbers of usability studies, the benefits of using more testing participants can be plotted as shown in Figure 26 (Nielsen 2000:1).

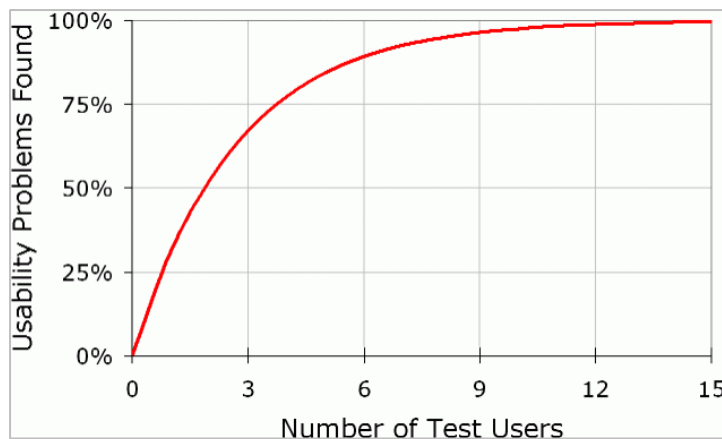


Figure 26: The diminishing return on number of testing participants (Nielsen 2000:1)

The current study adopted a strategy suggested by Nielsen (1994), which is that of extending the subgroup to include participants from different backgrounds, with regards to domain knowledge (Nielsen 1994). In order to categorise users into categories pertaining domain knowledge, the current study used previous experience with a domain rather than skill with a domain, since it is easier to define (Barnum 2010:5). The following categories were used as subject domains for classification:

- **Previous VR experience:** to collect a wider range of experiences, this study included participants with varying degrees of VR experience.
- **Previous computer gaming experience:** experience with (non-VR) computer/console games are often thought to have an impact on a user's experience of a VE, mostly due to their effect on spatial ability (Enochsson et al. 2004; Merchant et al. 2013), although

the full extent of this effect is still being debated (Khatri et al. 2014; Penn et al. 2017). Nevertheless, for the sake of completeness and for a better understanding of user behaviour, it was included as a domain knowledge qualifier for this study.

The subgroup only included participants who use computers frequently, since the results of the study are only applicable to VR-users and since it is assumed that VR-users are also frequent computer users. The current study thus made use of two subgroups: those with previous VR and/or computer gaming experience and those without. The ITC-SOPI questionnaire was used to divide users into these subgroups, as discussed in section 3.4.2.

As mentioned in section 2.3.2.2, the influence of psychological and physiological factors that arise from age, gender, nationality, and other demographic factors introduce significantly more complex variables into a study on VR and presence. Because of this, and because the effects of these factors are not its focus, the current study did not intentionally extend its subgroup to include and study different groups of people. The sampling details are discussed in section 3.3.2.4.

Regarding participant incentives, participants were given refreshments, both during the post-test interview and during the focus group.

3.3.2.3.3 How the system was tested

As mentioned in section 3.3.2.2, the test was a comparative, validation test, using within-subjects design and letting users move between tasks on their own. The basic procedure for each test was as follows:

1. The user signed an agreement allowing the use of data for study as well as being recorded, both on video during the test and using a voice recorder during the ensuing data collection, which is discussed in section 3.4.1.
2. The moderator (in this case, the researcher) discussed the procedure for testing, including the configuration of technologies for testing and data collection, their role in the study, the moderator's role in the study and any guidelines for how the participant should or should not behave during the test.
3. The participant was then assisted with the technology (in other words, with fitting the HMD), which signalled the start of the test.
4. Data were collected during the test by means of observation.
5. After the test, the participant was given a brief cooldown period, since they might have been wearing the HMD for some time.

6. More data were then collected in the form of the ITC-SOPI followed by a post-test interview, including categorising them based on VR- and/or gaming-experience, as discussed above.
7. When the interview was complete, the participant was given refreshments, which concluded the test with the participant.

One hour was allocated per user for the usability test and post-test data collection. In order to prevent a biased experience in the user during the test, the exact nature of the experiment was not explained to the user prior to the test, specifically the details regarding intersensory illusions, tactile feedback, and binaural audio. Instead, they were simply told that the purpose of the test was to investigate the perception of various sensory phenomena in VR. When referring to the test, the word “experiment” was always used to refer to the usability test itself, i.e. the participant performing tasks in VR. The reason for this was to prevent creating the impression in participants that their performances were being tested and instead frame their participation as an exploratory experience (Barnum 2010:1).

One important detail regarding the testing procedure that also needs to be discussed is that of the “think-aloud” protocol, which involves asking the user to (verbally) share their thoughts during the test to gain insight into their thought processes and decision-making processes (Barnum 2010:1; Pickard 2013:11). This method is a popular tool in usability testing (Rubin & Chisnell 2008:4; Barnum 2010:1; Pickard 2013:11), because instead of having to infer the reasoning behind a user’s behaviour, the user simply discusses their reasoning during the test (Rubin & Chisnell 2008:4; Barnum 2010:1). It also allows participants to recover from mistakes by talking themselves through problems they might have encountered (Rubin & Chisnell 2008:4).

However, thinking aloud has several drawbacks, such as the fact that participants might not be comfortable sharing all their thoughts while thinking aloud (Barnum 2010:2) or might not be entirely sure of their own mental processes (Rubin & Chisnell 2008:4). Additionally, it is unsure whether participants can intentionally incorporate thinking aloud while testing an interface without it affecting their behaviour (Hertzum 2016). Most notable, however, is the effect that thinking aloud could have on immersion and presence. As discussed in section 2.3.1.2, a high degree of immersion requires that a user is isolated from the real world (Witmer & Singer 1998), only receives stimuli regarding the VE (Slater 2003), and is minimally affected by factors originating from the real world which might distract their presence in the VE (Slater & Wilbur 1997). If the system accomplishes all of these factors, the system is said to be “inclusive” (Slater, Usoh & Steed 1995). By being asked to verbalise their thoughts, participants could feel that they are involved in some degree of conversation with

the moderator, or at the very least be constantly reminded of their presence in the real world, since their words could be heard by people in the real world.

Thus, for the purposes of the current study, the think-aloud protocol was regarded as a potential threat to immersion and presence and was thus not encouraged. If, however, a participant were naturally inclined (without input from the moderator) to verbalise their thoughts, as some people are wont to do while being tested (Rubin & Chisnell 2008:4), they were not discouraged as this could also have a similar negative effect of disrupting presence. Instead, the moderator made it clear at the start of the test that once the test has started there would be no interaction, verbal or otherwise, between the participant and the moderator.

3.3.2.3.4 The logistics of the test

The first logistical issue that needs to be addressed is the location where the testing took place, which was in the University of Pretoria's Virtual Reality and Interaction (VRI) Lab. The lab offers enough space to comfortably fit several VR-users simultaneously (although only one was tested at a time) and has been set up to accommodate the use of VR equipment in a private and relatively noiseless environment. The lab thus offers enough space for a test participant to move around freely as well as space for the moderator to comfortably observe the participant without getting into their way and for all the additional equipment required for video capture.



Figure 27: A work- and test-space at the VRI Lab at the University of Pretoria

The details of the equipment, both hardware and software, that was used for the usability test are discussed in chapter 4.

3.3.2.3.5 The role of the moderator during testing

As discussed in section 3.3.2.3.3, the moderator did not interact with the participant at all once the test has started and only interacted with the participant again once the test has been completed. The only circumstances under which the moderator intervened during the test was in case of a technical failure, due to hardware or software problems, which, as discussed, would be harmful to presence. Thus, the moderator played a minimal role during the actual test and only interacted with the participant before the test, to explain procedures, get the user to sign the agreement form, etc., and afterwards during the post-test data collection.

3.3.2.4 Sampling

Given that the current research is targeted towards any and all VR users, it would be impossible to involve the entire population, i.e. every person that the research can be applied to, in the study (Marshall 1996; Pickard 2013:5). Thus, it was necessary to use a sampling method for usability testing, which involves selecting a number of participants from the population to take part in the study (Pickard 2013:5; Preece, Sharp & Rogers 2015:7). The current research made use of purposive sampling when selecting participants for the interview, which requires the researcher to choose which participants to include in the sample based on what is required for the research (Marshall 1996; Morgan, Krueger & King 1998:6; Pickard 2013:5). The choice to use purposive sampling stemmed from the qualitative nature of the study, which aimed for depth of understanding, rather than generalisability, as well as the need to involve certain groups of participants, as identified in section 3.3.2.3.2, which would make a randomised sample inappropriate (Marshall 1996; Morgan, Krueger & King 1998:6; Pickard 2013:5). Furthermore, purposive sampling allows the researcher to choose participants who will deliver the most in-depth data regarding the research topic, also called “information rich” cases, who are expected to give the most insight into the topic under study (Morgan, Krueger & King 1998:6; Pickard 2013:5).

The need to involve certain groups of participants also motivated the use of an a priori sampling method, which uses an established sample framework based on the purposes of the study, which is then used to select participants (Pickard 2013:5). The reason for choosing this method stemmed from the need of the current study to investigate certain user groups, which required a pre-established sampling framework (Pickard 2013:5). While a priori sampling restricts the development of inductive sampling (Pickard 2013:5), the focus of the current study was not to develop emerging theory from the data collection and analysis, in other words, the study did not take a grounded theory approach, which made inductive sampling

inappropriate (Corbin & Strauss 2014:5; Taylor, Bogdan & DeVault 2015:2). Furthermore, a priori sampling was most appropriate for studying similarities and differences between groups, which was useful for the current study's use of classifying users into subgroups, and also provided some degree of security, as it covered all the required bases for the goal of the study and works better within a limited timeframe (Pickard 2013:5). The final sample size for the interviews was 23 participants.

For the focus group, convenience sampling was used to select participants from the interview sample, with the focus being on the ease with which the researcher can gain access to the sample (Morgan, Krueger & King 1998:2; Pickard 2013:5). The motivation for this was the logistical difficulty of requiring a number of individuals to simultaneously attend a group meeting, since many of these individuals could be working and/or studying full-time. A notable disadvantage of convenience sampling is that this method is only really appropriate when the criteria for sampling are virtually non-existent, in other words, anyone would be appropriate for the sample, which is generally rare when sampling from a larger population (Morgan, Krueger & King 1998:2). However, since the purposive sampling used to select participants for the interview already identified desirable candidates, selecting from this sample would also include participants with desirable traits, such as previous VR- and/or gaming-experience. The final sample size for the focus groups, out of the 23 interview participants, was ten participants, with four in the "previous VR and/or computer gaming experience" category and six in the "no previous VR and/or computer gaming experience" category, as discussed in section 3.3.2.3.2.

With the details of the research methods discussed, the specifics of the data collection that took place during and after the research methods are discussed next.

3.4 Data collection

In order to gather a wider range of experiences of perspectives and gather different types of data that complement one another, the current study combined a number of data collection methods (Preece, Sharp & Rogers 2015:7). Each data collection method is described below along with the reason for choosing it and which data it contributed to the study.

3.4.1 Observations

Although most data collection methods involve some sort of observation, ranging from casual to formal observation of events taking place, observation as a standalone data collection method refers to the focused and deliberate observation and recording of events by a researcher (Pickard 2013:19; Taylor, Bogdan & DeVault 2015:3). The raw data of doing

observation often take the form of descriptive notes made by the observer which attempt to capture a series of events or interactions that took place within a specific context, thus giving insight into the nature of the context, the behaviour of one or more persons within that context, or any other insights that can be gleaned from a researcher deliberately studying phenomena (Barnum 2010:5; Pickard 2013:19; Taylor, Bogdan & DeVault 2015:3).

In the context of usability tests, observation involves observing how users use a system/interface, including their nonverbal cues, such as facial expressions, body language, and utterances (Barnum 2010:5). For the current study, observation took place during the usability tests to gain insight into the behaviour of users during the tests themselves and to gather data to be used for triangulation with the other data collection methods (Taylor, Bogdan & DeVault 2015:3). A significant advantage of observation to be used during triangulation is that it reveals how users actually behave as opposed to how they claim to behave, since user behaviours do not always correspond with their descriptions or explanations (Punch 2001; Holzinger 2005; Corbin & Strauss 2014:3). There are a number of possible reasons for this, such as that users exaggerate or distort their accounts of events to put themselves in a certain light (Taylor, Bogdan & DeVault 2015:3) or that they might themselves have false perceptions about their own behaviour or be unable to articulate said behaviour (Corbin & Strauss 2014:3).

The usefulness of data obtained from observations has some limitations. Since all observation takes place from the perspective of the researcher, it can bring the objectivity of the researcher, and by extension the research, into question (Pickard 2013:19). Because the researcher is responsible for capturing data regarding events and interactions, the researcher must use their own judgement, and sometimes their own tacit knowledge, to decide which of these events and interactions are important and meaningful, which can lead to false positives when not triangulated with other collection methods, such as interviews (Pickard 2013:19; Corbin & Strauss 2014:3). Furthermore, as much as observation aims to be as unobtrusive as possible, it is inevitable that the act of observing, in any of its various forms, will influence the behaviour of individuals being observed to some degree (Pickard 2013:19). These aspects highlight the role of the researcher as instrument, placing the results of observation in the context of qualitative research.

Observation can be classified into different types regarding the interaction the observer has with the participant (direct/indirect observation), the setting of the observation (field/laboratory study), and the degree of involvement the observer has with the participant (participant/semi-participant/non-participant observation) (Pickard 2013:19; Preece, Sharp & Rogers 2015:7; Taylor, Bogdan & DeVault 2015:3). In the case of indirect and direct

observation, in other words, whether a researcher is (indirectly) observing with the use of mediating technology (Preece, Sharp & Rogers 2015:7), such as watching a video recording of a usability test at a later time (Holzinger 2005; Taylor, Bogdan & DeVault 2015:3), or (directly) without this mediating technology (Pickard 2013:19; Preece, Sharp & Rogers 2015:7), the use of the two types are not mutually exclusive, since one can both observe participants directly and collect information from indirect sources (Punch 2001; Preece, Sharp & Rogers 2015:7).

Thus, to capture a more complete account of user behaviour, participants were initially observed directly while interacting with the system while indirect data collection in the form of screen capturing was used for later analysis. Pilot testing indicated, however, that participants might feel self-conscious about their behaviour if observed directly. For this reason, video- and screen-recording were the only observation methods used. Screen capturing software allows to record the output of a system as it appears on a computer screen to a video file (Brick & Holmes 2008). For the current study, the screen capturing software captured the participant's first-person view from "within" the VE, in other words, what they choose to look at and were therefore seeing at any given moment. Participants themselves were also recorded using a video camera during the test to capture their behaviour in the form of real-world movements and interactions, as this allows for the capturing of large amounts of data for later analysis (Holzinger 2005) and can also allow for capturing user behaviour and interactions in more detail (Preece, Sharp & Rogers 2015:7). These data, synchronised with the screen recording data, provided a rich account of their interactions and reactions while performing the usability test.

However, since being recorded in this way could also make participants more self-conscious about their own behaviour and thus influence the results (Preece, Sharp & Rogers 2015:7), the data from the video recordings were also investigated for signs of participants visibly adjusting their own behaviour for the video camera (Preece, Sharp & Rogers 2015:7). It was also expected that this problem would be at least partially mitigated by the fact that participants were not able to see their environment and the video camera while wearing the HMD and the amount of attentional resources that the participant might allocate to the virtual environment, which might have made them less consciously aware of the physical environment (Bystrom, Barfield & Hendrix 1999).

With regards to the setting of the observation, while observing participants in their normal, everyday lives and settings provides benefits such as allowing the researcher to gain a deeper understanding of how systems/interfaces are used in real settings (Preece, Sharp & Rogers 2015:7), the fact that the resurgence of VR is still in its infancy (see section 2.1.2.2) means that

VR technologies have not yet gained mass adoption in the home or workplace, therefore there is not enough of a “field” to do field observation in. Thus, a laboratory setting was used when conducting usability tests, which allows replicability of the tests, since researchers have more control over laboratory conditions, which allows for a more objective stance from the researcher during testing (Preece, Sharp & Rogers 2015:7). However, the formality of the lab setting is expected to intimidate some participants or influence their behaviour during the test, which negatively impacts the generalisability of the results (Preece, Sharp & Rogers 2015:7).

As already discussed in section 3.3.2.3, the researcher had minimal interaction with the participant after having the participant sign consent forms and having explained the test procedure to the participant, therefore the researcher assumed the role of a “passive observer” during the test (Preece, Sharp & Rogers 2015:7). Again, this allowed for the researcher to act more objectively, which is expected to minimise the effect that the observer and act of observation would have on the participant by having the researcher not draw attention to themselves (Pickard 2013:19; Preece, Sharp & Rogers 2015:7).

As mentioned above, some of the limitations of observation are addressed by using them in tandem with other methods, which, for the current research, were questionnaires and interviews.

3.4.2 Questionnaires

A questionnaire can broadly be defined as a set of questions that are administered with the aim of obtaining data for the purposes of a study (Merriam-Webster 2018c; Oxford 2018f), which, in the context of a usability test generally refers to collecting subjective user data, such as satisfaction and preferences (Holzinger 2005). Questionnaires can take many forms, such as being paper-based or electronic (Pickard 2013:18; Preece, Sharp & Rogers 2015:7) and is one of the most used data collection methods (Pickard 2013:18; Preece, Sharp & Rogers 2015:7). Advantages of using questionnaires include their relatively low cost (Pickard 2013:18), their ability to reach a greater number of participants than most other methods and collect data remotely (Pickard 2013:18; Preece, Sharp & Rogers 2015:7), and the fact that the data obtained from questionnaires can be used to compile statistical measures (Holzinger 2005).

Using questionnaires also presents several disadvantages, perhaps the most notable being their relatively low response rate, in the case where questionnaires are distributed to a larger population (Pickard 2013:18). Questionnaires are also generally unsuited for obtaining rich, descriptive data due to the fact that participants tend to write as little as possible when

answering complex questions, which makes them more suitable for examining breadth over depth, in other words, for asking many simple questions rather than a few complex questions (Pickard 2013:18). Additionally, due to the fact that it is an indirect technique, in other words, it collects user-data stemming from using an interface rather than data about the interface itself, the answers given by participants are subject to their own fabrications and distortions (Holzinger 2005), which provided motivation for using this method in tandem with other methods, such as observation (Preece, Sharp & Rogers 2015:7).

Instead of creating a new questionnaire, the current study made use of an existing questionnaire that has been created for the purpose of obtaining a reliable and consistent presence measure across various research contexts: the ITC-Sense of Presence Inventory (Lessiter et al. 2001). (It should be noted at this point that the researcher was granted written authorisation to use the ITC-SOPI by the authors after agreeing to the copyright conditions associated with its use.) The ITC-SOPI was chosen as a presence measure since the concept of presence as the driving factor for the formulation of the questionnaire is similar to the current study's notion of presence as a subjective and illusory manifestation and as a separate construct than the media form variables that constitute the system that aims to create the feeling of presence (Lessiter et al. 2000; Lessiter et al. 2001). Although the ITC-SOPI does contain one open-ended question allowing participants to add any thoughts regarding their overall experience, the questionnaire primarily uses rank order questions, specifically Likert scales (Rubin & Chisnell 2008:8; Pickard 2013:18), which gauge participants' presence levels across multiple factor scores (Lessiter et al. 2001).

The website is visually appealing

strongly agree agree OK disagree strongly disagree

Figure 28: The use of a Likert scale to measure the intensity of a participant's attitude (Preece, Sharp & Rogers 2015:7)

However, the current study used a slightly modified version of the ITC-SOPI, with all questions regarding participant demographics, i.e. age, sex, occupation, and nationality (Lessiter et al. 2001) removed due to ethics concerns, although the questionnaire was still used to collect the name and contact details of the user, which were used to contact them for focus group arrangements. One question regarding virtual characters was also omitted from the questionnaire, as per the recommendations accompanying the ITC-SOPI, since the

prototype did not make use of any virtual characters. This questionnaire was also used to gain insight into each user's media-experience to use for classification purposes for the focus groups, which is discussed in section 3.4.4. The questionnaire was administered directly after the usability test (after the cooldown period) and was thus a post-test questionnaire (Rubin & Chisnell 2008:8; Barnum 2010:6).

For more in-depth qualitative data, interviews were also used as a data collection method.

3.4.3 Interviews

As mentioned above, an interview was conducted with each test user at the end of every usability test. An interview can broadly be defined as a face-to-face meeting between a number of people, usually centred around a specific goal, such as testing an individual to be suitable for a job or to gather information from one or more individuals (Cambridge 2018c; Oxford 2018e). In a qualitative research context, the definition is similar, with the goal being for the researcher to gather information about or understand a person's perspectives, views, experiences, etc. (Barnum 2010:6; Taylor, Bogdan & DeVault 2015:4).

Interviews can be used to obtain in-depth views and understandings of people's perceptions and experiences and is often used to obtain qualitative data that are complex and not easily answered (Punch 2001; Pickard 2013:17; Taylor, Bogdan & DeVault 2015:4). Interviews are appropriate for the qualitative methodology's approach to viewing the researcher as a research instrument, since it is assumed that the process of being interviewed as well as the interviewer themselves will inevitably have some effect on the interviewee's insights and meanings constructed from events (Pickard 2013:17; Taylor, Bogdan & DeVault 2015:4). Doing interviews as opposed to written data collection for qualitative data offers some significant advantages, such as the fact that people will usually write as little as possible when having to write down the answer to a question, whereas they tend to provide much longer answers when asked to answer verbally (Pickard 2013:17). Interviews can also capture unexpected data in the form of nonverbal cues, such as facial expressions (Corbin & Strauss 2014:3).

Interviews are often classified in terms of their structures, i.e. how closely they follow a plan/structure (Barnum 2010:6; Pickard 2013:17; Corbin & Strauss 2014:3; Preece, Sharp & Rogers 2015:7). At one extreme, structured interviews rely purely on a set of pre-established questions which are given to each interviewee (Barnum 2010:6; Preece, Sharp & Rogers 2015:7) and are, for this reason, sometimes referred to as "researcher-administered questionnaires" (Pickard 2013:17). The structure of the interview provides a level of consistency and saves time both during the interview and also by allowing the interviewer to

pre-code their data, which saves time during data-analysis (Pickard 2013:17; Corbin & Strauss 2014:3; Preece, Sharp & Rogers 2015:7).

Unstructured interviews, on the other hand, take on the form of a purposeful conversation about a specific topic (Pickard 2013:17; Preece, Sharp & Rogers 2015:7) and focus on highly individualised information, such as the interviewee's thoughts, feelings, and memories, which differs significantly from pure factual data (Pickard 2013:17; Taylor, Bogdan & DeVault 2015:4). Unstructured interviewing is also interactive and flexible, which is useful when dealing with unpredictable human factors (Pickard 2013:17; Taylor, Bogdan & DeVault 2015:4) and allows interviewees to have some degree of influence over the interview, thus allowing them to discuss topics which they think are important, but which the interviewer might have missed (Corbin & Strauss 2014:3; Preece, Sharp & Rogers 2015:7). However, similar to open questions in questionnaires, unstructured interviews are subject to answers from interviewees that might include fabrications, exaggerations, and distortions that put them in a certain light or by providing the answers which they think the interviewer wants to hear (Preece, Sharp & Rogers 2015:7; Taylor, Bogdan & DeVault 2015:4).

A middle-way between the two extremes is the use of semi-structured interviews, which make use of a predetermined checklist/guide that ensures that all the required topics are covered by the interviewee, although this checklist does not necessarily govern the order or pace of the interview (Pickard 2013:17; Corbin & Strauss 2014:3). Thus, the interviewer still has the structural freedom to pursue avenues in the conversation that they might consider not important or not yet fully explored (Pickard 2013:17). The current study made use of a semi-structured interview, because it was essential that the interview cover a list of topics predetermined by the focus of the study and gleaned from the literature. Because of this need to address issues from the research focus, the degree of consistency provided by a semi-structured interview was also needed. However, the interview still needed to be rooted in qualitative data, since participants' experiences needed to be explored, which meant that the interview made use of open-ended questions.

The interview took place directly after the ITC-SOPI has been filled in and was recorded with a Zoom H2n audio recorder (Zoom 2013) for the sake of having all interviews on record and to free the interviewer from taking notes, allowing the interviewer to pay closer attention to the interviewee (Preece, Sharp & Rogers 2015:7). The interview started with a primer explaining the purpose of the interview and that there are no specific right or wrong answers to any of the questions and that the interview only focuses on their honest opinions and experiences after using the VR system. The terms of the voice-recording and confidentiality of the data were then explained to them and they were asked if they had any questions before

the interview started. The list of questions which were used as a guideline/checklist, as per the method for conducting a semi-structured interview (Pickard 2013:17; Corbin & Strauss 2014:3), can be found in Appendix B. The interview took place in English or Afrikaans, depending on the preference of the interviewee, in order to let participants express themselves comfortably and naturally.

The last data collection method, which does not appear in the usability test plan, was focus groups conducted as a follow-up method to the usability test, which is discussed next.

3.4.4 Focus groups

Focus groups can roughly be defined as (research) interviews that take place in a group setting and, similar to individual interviews, are used to gather data in the form of opinions and insights regarding a specific topic, which originates from group discussions that occur during the focus group session (Morgan, Krueger & King 1998:1; Pickard 2013:21; Preece, Sharp & Rogers 2015:7). As such, focus groups usually tend towards being open-ended interviews, aimed at free-form discussion rather than a strict guided probe (Morgan, Krueger & King 1998:1; Taylor, Bogdan & DeVault 2015:4). The groups usually consist of about three to ten people who are chosen to be representative of the sample population and are usually grouped by having similar backgrounds or experiences (Morgan, Krueger & King 1998:1; Preece, Sharp & Rogers 2015:7; Taylor, Bogdan & DeVault 2015:4). Although group dynamics are difficult to keep record of, focus groups are often recorded, for example, using an audio recorder (Pickard 2013:21; Preece, Sharp & Rogers 2015:7).

Apart from the fact that they involve groups of individuals, focus groups also differ from interviews in the role that the researcher plays, which is that instead of assuming the role of the interviewer, they assume the role of the moderator/facilitator (Morgan, Krueger & King 1998:1; Pickard 2013:21; Preece, Sharp & Rogers 2015:7). Instead of merely engaging in two-way communication as in the interview (Morgan, Krueger & King 1998:4), the moderator guides the multiway conversation between themselves and participants as well as among participants while also prompting them for answers (Morgan, Krueger & King 1998:4; Pickard 2013:21; Preece, Sharp & Rogers 2015:7). It is the responsibility of the interviewer to manage contributions from and interactions between participants and in doing so to create a suitable group dynamic for the research setting and the data that need to be collected (Morgan, Krueger & King 1998:1; Taylor, Bogdan & DeVault 2015:4). Examples of this include preventing participants from arguing or interrupting each other as well as preventing overly talkative members from dominating the conversation and thus dissuading less talkative participants from talking at all (Pickard 2013:21; Taylor, Bogdan & DeVault 2015:4).

Moderators also bring their own tacit knowledge to the session, including their cultural and ethnic knowledge stemming from their background, and as such they have a significant impact on the data and the quality thereof that is produced by the session (Morgan, Krueger & King 1998:1). However, moderators must refrain from becoming participants or displaying their own knowledge of a subject domain by, for example, appearing condescending towards participants, since the moderator never assumes a teaching role, only a learning role (Morgan, Krueger & King 1998:1; Morgan, Krueger & King 1998:4).

Due to the group-nature of a focus group, the goal is not for the group to reach a consensus on a topic, but rather to collect a diverse set of opinions and perspectives within a population (Pickard 2013:21; Taylor, Bogdan & DeVault 2015:4; Preece, Sharp & Rogers 2015:7). In fact, in the context of a focus group, conformity among participants is something to be purposefully avoided and goes against the purpose of using focus groups to begin with (Morgan, Krueger & King 1998:1). Rather, the focus is on exploring a set of topics and investigating experiences and beliefs in great depth by allowing participants to engage in conversation with one another, thus bringing their own perspectives and contexts into the discussion (Morgan, Krueger & King 1998:1; Rubin & Chisnell 2008:1; Taylor, Bogdan & DeVault 2015:4). The group dynamic introduces different lines of communication for data collection: between the moderator and participant(s) as well as between the participants themselves (Morgan, Krueger & King 1998:1).

Compared to individual interviews, they take less time to do when interviewing multiple people and thus produce larger amounts of data in a shorter amount of time; however, they produce less data per person than individual interviews, which presents both an advantage and a disadvantage as more data can lead to more insight, but takes longer to analyse (Morgan, Krueger & King 1998:1; Preece, Sharp & Rogers 2015:7). The main advantage provided by focus groups, however, is the group dynamic that helps participants form or express insights that might not have been possible without the discussions that take place within the group (Pickard 2013:21; Taylor, Bogdan & DeVault 2015:4; Preece, Sharp & Rogers 2015:7). This method relies on the fact that talking to others in a social context gives different ways to think of and approach concepts, thus letting participants discuss and develop these concepts in ways that would not have been possible in individual interviews, including altering and even completely reversing their views and opinions (Morgan, Krueger & King 1998:6; Pickard 2013:21; Taylor, Bogdan & DeVault 2015:4; Preece, Sharp & Rogers 2015:7). It also creates a supportive environment which could encourage participants to express a wide variety of opinions and experiences which they might have been tentative to express

otherwise and allows for a degree of flexibility regarding the structure of the discussions (Morgan, Krueger & King 1998:1; Preece, Sharp & Rogers 2015:7).

However, this group dynamic can also have negative consequences for data collection: participants' opinions can be shaped by group dynamics in various ways, for example, by adjusting their own opinions to fit more with what other group members are saying (Taylor, Bogdan & DeVault 2015:4). Furthermore, similar to interviews, participants might adjust their answers based on what they think the moderator would want to hear or to put themselves in the best light (Morgan, Krueger & King 1998:1; Preece, Sharp & Rogers 2015:7; Taylor, Bogdan & DeVault 2015:4). In fact, focus group moderators often experience a magnified version of this phenomenon, as participants discuss and agree on each other's likely behaviours, which might or might not actually end up materialising (Morgan, Krueger & King 1998:1). Additionally, focus groups are not as private as individual interviews, which might affect which information participants choose to share, especially if participants already have established relationships before the session, for example, if they are colleagues (Morgan, Krueger & King 1998:1).

Two key concerns for creating and nurturing group dynamic are 1) the compatibility between members of the same group and 2) how the larger sample gets divided/segmented into groups; referred to as compatibility and segmentation respectively (Morgan, Krueger & King 1998:2). Compatibility can be defined as the extent to which participants view each other as being fundamentally similar, which plays a significant role in the extent to which participants feel comfortable being and discussing amongst each other in the group (Morgan, Krueger & King 1998:2). Compatibility is often achieved by grouping participants by similarities, such as demographics or, more importantly, experiences, in order to create homogenous groups (Morgan, Krueger & King 1998:2). While compatibility is established to focus on the priorities of the group, segmentation is established to focus on the priorities of the researcher, in other words to gather a larger set of distinctive perspectives and opinions (Morgan, Krueger & King 1998:2). Participants may be divided and grouped based on several characteristics, such as demographics or having different perspectives, experiences, or attitudes toward something, although the last one may be harder to define (Morgan, Krueger & King 1998:2). Dividing and grouping participants depends on the type of data researchers want to gather from the participants, for example, by dividing them according to experience with a technology, groups can be more comfortable discussing the technological factors, since their group members share the same amount of experience with them and this also allows researchers to gain unique insights from each group based on their level of experience with the technology (Morgan, Krueger & King 1998:2).

Like both the previous methods discussed, focus groups can also be divided into types, which can be broadly categorised as being more structured or less structured (Morgan, Krueger & King 1998:2). More structured focus groups make use of a set of well-defined questions that need answers and present participants with strict time allocations for each question to be answered (Morgan, Krueger & King 1998:2). This method saves time and thus allows a researcher to cover more topics in a set timeframe, but underutilises a unique aspect of focus groups, which is that more structured focus groups do not allow participants to raise issues of their own that the researcher might have missed, thus underutilising a large part of the exploratory nature of focus groups (Morgan, Krueger & King 1998:2). Conversely, less structured focus groups are the most open-ended way to conduct group interviews, relying less on a set of questions and more on topics of interest that need further investigation and lead to asking the correct questions rather than seeking answers for the questions themselves (Morgan, Krueger & King 1998:2). However, while the discussion is always kept on the main topic tied to the research, it can become erratic and thus make it hard for moderators to tell whether the discussions are generating valuable data and can also make it hard for researchers to compare data between different groups for analysis (Morgan, Krueger & King 1998:2; Pickard 2013:21).

Faced with two extremes, researchers often choose to compromise, thus choosing a moderate degree of structure for their focus groups (Morgan, Krueger & King 1998:2). When using these moderately structured focus groups, one can adopt the strategy of what is called the “funnel design”, which refers to starting the discussion with broader topics and narrowing them down as the discussion progresses, such as beginning with usually one or two wide-open questions that allow the group to explore issues to be discussed, moving on to usually three or four questions that are more directly in line with the researcher’s goals, and finally reaching a larger number of specific questions that are more structured and central to the topic (Morgan, Krueger & King 1998:2). With regards to spurring on discussions, focus groups can also make use of questions that are prepared and asked in full, i.e. the questioning route, or use broader topics or outlines which then provide entry points for discussion, i.e. the topic guide (Morgan, Krueger & King 1998:3).

The current study made use of focus groups as a follow-up measure for both the observations and interviews (Barnum 2010:6). Since the focus groups took place close to the end of the research process, they were used to seek explanations for observed behaviours, explore conflicting views from interviews and confirm preliminary findings from both methods (Pickard 2013:21). The focus groups for the current study were moderately structured, using the funnel design, and made use of the questioning route for asking questions. The reason for

using the funnel design is that starting with questions that are wide open set the tone for the session, allowed the groups to get comfortable with the discussion, and could provide unanticipated insights into their experiences, which could be discussed later (Morgan, Krueger & King 1998:2; Taylor, Bogdan & DeVault 2015:4). However, the focus group still emphasised the use of more specific questions to directly address the topic of the study, since the goal of the focus group was to address specific issues rather than gain broad insight into a general issue. This also formed part of the reason for using the questioning route, since using more specific questions allowed the moderator to hone in on more specific issues, rather than broad ones (Morgan, Krueger & King 1998:3). Other reasons for choosing this method include allowing for better comparative analysis of data due to the consistency between group sessions and the fact that the researcher is not experienced in moderating focus groups (Morgan, Krueger & King 1998:3).

In order to maximise compatibility and make appropriate use of segmentation (Morgan, Krueger & King 1998:2), participants were divided into groups based on their previous VR- and/or gaming-experience, with one group consisting of participants with previous VR- and/or gaming-experience and the other group consisting of those without. The reason for this distinction was to create groups that view each other as similar based on their experience or inexperience in these areas and to allow experienced users to share terminology and perspectives in order to achieve more in-depth discussions about their experiences more quickly and easily while separating experienced and inexperienced participants to avoid inexperienced users feeling alienated and left out from discussions involving terms and experiences they cannot relate to (Morgan, Krueger & King 1998:2). It also allowed questions to be set up slightly differently for either group in order to quickly establish a set of common terms for the experienced participants to express their experiences, while again preventing inexperienced participants from feeling alienated by purposefully avoiding any jargon and technical terms in the wording of the questions (Morgan, Krueger & King 1998:3). However, to avoid significant differences in meaning between the questions for either group, these differences were kept to a minimum and were taken into account during analysis (Morgan, Krueger & King 1998:3).

The focus groups were held at the University of Pretoria's Virtual Reality and Interaction (VRI) Lab, since this lab is large enough to host a focus group and has a table which allows the researcher and participants to face each other while having a discussion (Morgan, Krueger & King 1998:2). As discussed in section 3.4.2, the ITC-SOPI was used to obtain the participant information to be used for segmentation. The focus group sessions were also recorded using a Zoom H2n (Zoom 2013) audio recorder for recordkeeping and analysis

(Preece, Sharp & Rogers 2015:7). Similar to the interviews, each focus group session started with a primer explaining that there are no specific right or wrong answers to any of the questions and that the focus group only focused on their individual opinions and experiences after using the VR system. The questions that dictated the pre-established structure of the focus group session can be found in Appendix D. The focus group also made use of a technique known as retrospective recall, which is discussed next.

3.4.4.1 Retrospective recall

Focus groups, as well as interviews, often take place in neutral and artificial environments, such as office rooms or dedicated rooms for discussion (Morgan, Krueger & King 1998:1; Barnum 2010:2; Preece, Sharp & Rogers 2015:7). To reduce the potentially stifling effect that such an artificial environment can have on participants, focus group moderators can bring extra materials related to the study, such as task descriptions or recordings of the test, to aid discussion (Rubin & Chisnell 2008:4; Preece, Sharp & Rogers 2015:7). Using the latter to guide discussion is known as retrospective recall (Barnum 2010:6) or retrospective review (Rubin & Chisnell 2008:4) and is a form of post-test interview in which participants are shown records of their performance which then provides a basis for discussion (Rubin & Chisnell 2008:4; Barnum 2010:6). Two methods exist for capturing and discussing user tests for retrospective recall (Rubin & Chisnell 2008:4):

- **Manual method:** using this method, the researcher revisits their notes taken during the test which describe the participant's actions. These notes are used to remind the participant about every notable occurrence during the test which they may have forgotten and help them relive the experiences and emotions they had during the test. This method generally requires the researcher to take a lot of notes during the test and remember crucial moments in order to discuss these afterwards with the participant.
- **Video method:** this method requires the researcher to record the usability test on video, which is then watched with the participant, allowing them to see their own behaviour, facial expressions, etc., making it easier to remember their own experiences, emotions, etc. This allows for a less obtrusive test, as participants need not be interrupted in order to get them to verbalise their thoughts or explain their actions, but can also make analysis very time consuming, as a potentially large amount of video might have to be watched through.

Retrospective recall can also be used as a substitute for the think-aloud protocol to a degree, since participants are asked to verbalise their thought processes, decision-making, etc., albeit after the test instead of during (Rubin & Chisnell 2008:4; Barnum 2010:6). There are also situations where retrospective recall would be more appropriate than thinking aloud, such as

when thinking aloud could have a negative effect on the participant's concentration (Barnum 2010:6). The most notable disadvantage of using retrospective recall is that it significantly increases the time required for usability testing, potentially even doubling the time required, especially, as mentioned above, in the case of using video recordings for review (Rubin & Chisnell 2008:4; Barnum 2010:6).

Due to ethics concerns, the current study refrained from using the video method and instead relied on notes derived from the observation of the experiments in order to guide discussion and provide a basis for participants to recall their own experiences during the test (Rubin & Chisnell 2008:4; Barnum 2010:6). The notes to be discussed were selected before the focus group and focused on specific participant behaviour and experiences that were potentially significant for the outcome of the study. The selected notes also served to establish common grounds between participants and to allow the participants whose behaviours are discussed to elaborate on their own experiences, thus stimulating recall from different participants in order to promote discussions of different experiences and perspectives (Rubin & Chisnell 2008:4; Pickard 2013:21).

3.4.5 Use of multiple data collection methods

Apart from triangulation for the sake of credibility (Pickard 2013:19; Corbin & Strauss 2014:3), each data collection method served a unique purpose in the context of the current study:

- **Observations:** since it was expected that the experience of using VR might be novel or strange to participants, it is expected that some might not have been able to adequately express their experiences during the interviews or focus groups (Corbin & Strauss 2014:3). The combination of video- and screen-recordings thus provided an account of their experience with which to supplement the experiences they have difficulty expressing or might have forgotten or deemed irrelevant.
- **Questionnaires:** apart from gauging the amount of presence experienced during the usability test, the data from the questionnaires were also used for user experience and heuristic measures, which are discussed in sections 4.2.2.2 and 5.2.1. They also served to indicate the levels of possible negative factors that participants might experience, such as motion sickness or fatigue.
- **Interviews:** the data from conducting interviews constituted the bulk of the research data, which were used to draw preliminary conclusions and build concepts (Corbin & Strauss 2014:4) that could be tested with participants during the follow-up method, i.e. the focus groups (Barnum 2010:6).

- **Focus groups:** as a follow-up method, the focus groups were used to provide insight into preliminary conclusions drawn from the triangulation of other methods, such as confirming or challenging inferences made from observations, questionnaires, and interviews (Barnum 2010:6).

Having established methods for the collection of data, the following section introduces the methods to be used for analysis of said data.

3.5 Data analysis

As discussed in section 3.1, quantitative data collection methods produce numerical data, which rely on rigid, systematic analysis methods, such as statistical analysis (Roberts 2010:2; Pickard 2013:24). Qualitative data collection, on the other hand, produces descriptive data regarding experiences, emotions, and other humanistic data, which cannot be analysed using those methods (Pickard 2013:1; Corbin & Strauss 2014:2). In stark contrast to those of quantitative analysis, qualitative analysis methods resist formalisation and cannot be reduced to a technical, rigid process (Corbin & Strauss 2014:4; Taylor, Bogdan & DeVault 2015:6).

Instead, qualitative analysis involves the interpretation of data by the researcher in order to gain a deeper understanding of the experiences, emotions, phenomena, etc. that are described by the data (Morgan, Krueger & King 1998:6; Pickard 2013:23; Corbin & Strauss 2014:4). This interpretation occurs alongside data collection (Morgan, Krueger & King 1998:6; Pickard 2013:23) as the researcher constantly assesses and interprets incoming data against other data, records their understanding (using, for example, analytical memos), and continues this process as more data are collected and analysed (Harding 2013:4; Taylor, Bogdan & DeVault 2015:6). This concurrent process of collecting data, interpreting it, and possibly letting it influence the remaining data collection activities is a defining feature of qualitative analysis and makes it a uniquely flexible method for making sense of potentially large amounts of descriptive data (Corbin & Strauss 2014:4; Taylor, Bogdan & DeVault 2015:6).

As discussed at the start of this chapter, the current research embraces the role the researcher plays in interpreting and giving meaning to data collected, thus including the researcher as research instrument in reaching the goal of the study (Pickard 2013:1; Corbin & Strauss 2014:4). The researcher utilises their tacit knowledge of various scenarios, as well as possible life experiences that they might share with participants in order to interpret and understand the data from participants (Pickard 2013:1; Corbin & Strauss 2014:4). The researcher should also make use of their understanding of the emotions displayed by participants and use empathy in making sense of data from participants, since certain data in the form of descriptions, recollections, etc. might carry emotional weight for the participants, thus

signalling added meaning during analysis (Harding 2013:5; Corbin & Strauss 2014:4). (It is important to note that the data to be analysed refer strictly to that generated by the usability test itself and not by the data of the pilot study, which were not analysed).

One of the major caveats of this approach to analysis is the introduction of the researcher's own biases and worldviews into the process by which data are "mined" for value (Corbin & Strauss 2014:5). Although this use of existing worldviews and perspectives is one of the strengths of qualitative analysis (Corbin & Strauss 2014:4), it is also one of the largest threats to the value of the results as it could undermine the credibility and transferability of the results (Pickard 2013:1). Whereas quantitative studies aim for true objectivity in all phases including data analysis (Pickard 2013:1), it is argued that this type of objectivity is not possible in qualitative analysis due to the necessary involvement of the researcher in interpreting and understanding data to make assumptions (Corbin & Strauss 2014:5; Taylor, Bogdan & DeVault 2015:6).

Qualitative researchers thus always have the potential to influence the research results, both in the data collection and analysis phases (Corbin & Strauss 2014:5; Taylor, Bogdan & DeVault 2015:6). To counter this, researchers must be aware of this influence and attempt to distance themselves from the data through strict self-evaluation (Corbin & Strauss 2014:18) in order to think clearly and critically during analysis, perhaps even using their own tacit knowledge to challenge assumptions they might make during this phase (Corbin & Strauss 2014:5). This separation between the researcher and the data is used to ensure that, while the researcher themselves play an integral role in reaching conclusions from the data, other researchers should also, given the same data, be able to reach similar conclusions (Morgan, Krueger & King 1998:6), thus ensuring the confirmability of results (Pickard 2013:1).

Furthermore, the fact that analysis is interpretive and flexible does not mean it is done haphazardly or that decisions are made arbitrarily; to the contrary, it still follows an established process (Morgan, Krueger & King 1998:6). The flexibility of the qualitative analysis method stems from the sensitivity of this process to the scenario and the people involved (Corbin & Strauss 2014:4). Arguably the most commonly used of these analytical processes is what is called the constant comparative method (Pickard 2013:23; Harding 2013:4), which is discussed next.

3.5.1 Constant comparative analysis

Using comparisons as a tool to make sense of different data is usually an inherent part of qualitative analysis (Harding 2013:4; Corbin & Strauss 2014:5). This includes making sense of data from a single source by comparing different instances as well as making sense of data

from a variety of sources by comparing them and looking for similarities and differences (Harding 2013:4; Corbin & Strauss 2014:5). This process, inherent in most qualitative research, is made explicit in the form of constant comparative analysis, which, broadly speaking, involves the process of comparing discrete pieces of data to find similarities and differences and using these similarities and differences to gain understanding or build theory (Pickard 2013:23; Corbin & Strauss 2014:5).

In more detail, this process is started by breaking data into discrete units for analysis, such as paragraphs, sentences, or words, with each unit representing a concept which can be used for comparison (Pickard 2013:23; Corbin & Strauss 2014:5). Pieces of data that are conceptually similar are grouped together under conceptual labels/headings that represent the idea which unites each piece of data under said label through a process known as coding (Pickard 2013:23; Corbin & Strauss 2014:5). As a result of this grouping of data under conceptual labels, researchers can gain clearer understanding of how data under each label relate to other data under the same label, as well as how data between labels relate to each other; thus, researchers can use this grouping to find patterns in the data (Pickard 2013:23; Harding 2013:4; Corbin & Strauss 2014:5). Ideally, this process of labelling and grouping data is repeated until the point where new data stop adding new insights or understanding, in other words, when the point of “theoretical saturation” is reached (Harding 2013:4; Pickard 2013:23). However, in practice the decision to stop collecting and analysing data is more commonly driven by time and resource constraints (Harding 2013:4).

In order to describe the details of the constant comparative analysis method more thoroughly, the underlying process of coding is discussed next.

3.5.2 Coding

As discussed, making the implicit method of comparing different data explicit involves dividing data into discrete units, through a process known as coding (Pickard 2013:23; Corbin & Strauss 2014:5). Broadly speaking, coding involves assigning a code in the form of a number, symbol, abbreviation, word, or even a short phrase to a discrete unit of data, which then aligns that piece of data with others that are marked with the same code (Harding 2013:5; Taylor, Bogdan & DeVault 2015:6). This process is repeated for all data, the result of which is that each unit of data has been reduced to its core concept and has been aligned with all other units of data that share this core concept (Harding 2013:5; Taylor, Bogdan & DeVault 2015:6), or, concisely, that concepts have been denoted to stand for the meaning of different pieces of data (Corbin & Strauss 2014:4; Corbin & Strauss 2014:5). This process of assigning codes to pieces of data is often done with the use of dedicated software (Taylor,

Bogdan & DeVault 2015:6), such as Atlas.ti (<https://atlasti.com>) which was used for this purpose for the current study.

The word “concept”, in the context of coding, refers to a single generalised idea that results from the interpretation of data (Corbin & Strauss 2014:4; Corbin & Strauss 2014:12; Taylor, Bogdan & DeVault 2015:6). Concepts are used to group data that share interpreted meaning to aid the search for patterns and reduce the amount of raw data that researchers have to use to find these patterns (Corbin & Strauss 2014:12). As such, they are often developed by identifying commonalities between data units and using these to inform the creation of concepts used for generalisation (Harding 2013:5; Taylor, Bogdan & DeVault 2015:6). Furthermore, if one considers a single concept which contains a single piece of data to be a low-level grouping of pieces of data, then one can also devise higher-level groupings, which are called categories or themes (Harding 2013:5; Corbin & Strauss 2014:12). Categories are used to conceptually group multiple concepts under higher-level labels, which further aid in the management of raw data to search for patterns and relationships (Harding 2013:5; Corbin & Strauss 2014:12; Taylor, Bogdan & DeVault 2015:6).

As with all other aspects of qualitative research, coding relies on the interpretation of the researcher for the creation of concepts and categories and to assign pieces of data into these categories, which require data to be considered in context (Harding 2013:5; Taylor, Bogdan & DeVault 2015:6). Along with the number of times a concept appears in the data, i.e. the frequency of the concept, researchers should also account for the amount of people whose words or behaviour created the raw data denoted by the concept, i.e. the extensiveness of the concept, as well as the intensity of the point of view or behaviour that created the raw data, i.e. the intensity of the concept (Morgan, Krueger & King 1998:6), since the role of coding is not to produce countable occurrences to be used as evidence in favour of a hypothesis, but to create deeper understanding of the raw data for the researcher (Taylor, Bogdan & DeVault 2015:6). Thus, the coding process is not inherently methodical and does not concern itself with the accuracy of its categorisation, but rather reflects the conceptualisation of the researcher (Harding 2013:5; Taylor, Bogdan & DeVault 2015:6). The process, however, can be broken into several levels (Pickard 2013:23), which are discussed next.

3.5.2.1 Open coding

The initial stage of coding data is called open coding and involves reading through all existing data and beginning to assign codes to stand for the interpreted meaning of discrete units of data (Pickard 2013:23; Corbin & Strauss 2014:13). As conceptual labels are attached to units of data, the researcher also pays attention to other units of data that have similar labels, thus creating the aforementioned concepts that can be shared between many units of data (Pickard

2013:23). Properties and dimensions of concepts are also identified, with properties used to further describe and define concepts and dimensions discussing the range of change within properties, for example, the concept of flight can contain the property of duration, which can be measured, thus referring to its dimensions (Corbin & Strauss 2014:12). As concepts are created that match emerging themes in the data, the concepts are sorted into categories, which starts the process of axial coding (Pickard 2013:23).

3.5.2.2 Axial coding

At this point, concepts are sorted into categories, thus creating higher-level conceptual groupings which result from the researcher's interpretation based not only on the contents of the data, but also on the context in which the data were collected (Pickard 2013:23; Corbin & Strauss 2014:10). These categories also serve to aid the researcher in creating conceptual links between various concepts, including those between categories in order to discover patterns in the data (Morgan, Krueger & King 1998:6; Pickard 2013:23). Having identified the main categories that units of data can be logically grouped in, the next stage requires the selection of the main concept that is the focus of the research, which is called selective/focused coding (Pickard 2013:23; Taylor, Bogdan & DeVault 2015:6).

3.5.2.3 Selective coding

Also called focused coding (Taylor, Bogdan & DeVault 2015:6), this final stage of coding involves identifying the "core category" of the research, which tie together the main findings of the research from the data (Pickard 2013:23; Corbin & Strauss 2014:10). The core category is the refined, abstract category which should be able to explain the overarching ideas of all other categories and tie them together into a coherent theory (Pickard 2013:23; Corbin & Strauss 2014:10; Taylor, Bogdan & DeVault 2015:6). It is worth noting at this point that selective coding is largely applied in the development of grounded theory and is a required step for the development of theory that is grounded in the data (Pickard 2013:23). However, the current study did not use a grounded theory approach, since the focus of the study was not to develop emerging theory from the data collection and analysis (Corbin & Strauss 2014:5) and thus did not employ selective coding.

3.6 Summary

In this chapter the research methodology for conducting the research, along with the measures for establishing the value of the research, were discussed. The topic of software process models, including the one chosen for the development phase of the current study, were then discussed. The research method, as well as the preliminary research method, were then discussed, including the scope of what the current study considers falling under the term

“usability”, different types of usability tests according to various parameters, and which type the current study falls under, and finally the details and logistics of the usability test that the current study employed. This was followed by a discussion on sampling, as well as the sampling methods used for the current research. The various methods of data collection, observations, questionnaires, interviews and focus groups, were each explored in turn and the type and details of each to be used in the current study were selected. Finally, the analysis of the data from these methods was discussed by first discussing qualitative data analysis against quantitative analysis and then discussing the analysis method to be used as well as the processes that accompany this method. The next chapter discusses the details regarding the development of the software prototype to be used during the usability test and all the design choices regarding this software prototype.

4. Chapter 4 - System design and implementation

This chapter discusses the technical details regarding the implementation of the software prototype which implemented potential methods of inducing illusory tactile feedback through the use of intersensory illusions. Thus, this piece of software, which did not change throughout any of the research methods, was also the focal point of the usability test and is, from this point, referred to as the “prototype”. The discussion is divided into two main categories: the hardware details, which involves all the notable details regarding the hardware that enabled the software implementation, and the software, which involves all the notable details pertaining to the specific choices involved in implementing the potential methods of inducing illusory tactile feedback.

4.1 *Hardware details*

This section discusses all the hardware details that had a direct impact on the choices made during implementation and the experience of the user during the usability test itself. For the purposes of this study, three core aspects are discussed: the head mounted display (HMD), the interaction mechanism, and the device for delivering audio feedback, which in this case refers to the headphones used.

4.1.1 **Head-mounted display**

The HTC Vive (HTC Corporation 2018) was selected as the HMD to deliver an immersive VR-experience, the main reason for this being availability: the Virtual Reality and Interaction (VRI) Lab at the University of Pretoria provides access to an HTC Vive system. Since the Vive system itself consists of three separate components, or six if one counts each controller and base station separately (Niehorster, Li & Lappe 2017), each of these components are discussed separately.

4.1.1.1 *Headset*

This refers to the device the user wears on their heads which provides visual feedback to the user (HTC Corporation 2018). The headset costs 599USD as of September 2018 (HTC Corporation 2018) and its details are as follows (Niehorster, Li & Lappe 2017; HTC Corporation 2018):

- **tracking range:** 360° head-tracking
- **display resolution:** 1080 x 1200 pixels per eye
- **display refresh rate:** 90Hz
- **field of view:** 110°

- **pixel density:** about 12 pixels/°
- **end-to-end latency:** 22ms.



Figure 29: The HTC Vive headset (HTC Corporation 2018)

4.1.1.2 *Handheld controllers*

The HTC Vive system also includes two handheld controllers. These controllers are also tracked in the 3D space with 360° tracking in the space. However, the controllers were not used for the current study, the reason for which is discussed in section 4.1.2.

4.1.1.3 *Base stations*

Also called “lighthouses” (Niehorster, Li & Lappe 2017), the Vive’s base stations refer to two infrared laser emitters that come standard with the device (HTC Corporation 2018). The purpose of these devices is to emit laser sweeps horizontally and vertically, which collide with photodiodes on the surface of the headset, which track the position and rotation of the headset (Niehorster, Li & Lappe 2017). This enables the system to track the user’s position and rotation while the user moves freely within a designated area, called the “play area” (Niehorster, Li & Lappe 2017; HTC Corporation 2018). While the suggested maximum size of the play area is around 4.5m x 4.5m (HTC Corporation 2018), the system has also been found to deliver accurate tracking in sizes of up to 8m x 8m (Niehorster, Li & Lappe 2017). The play area created by the base stations also offer what is called a “chaperone system”, which gives a visual indication to the user, in VR, when they are approaching the edges of the physical space (HTC Corporation 2018).

4.1.2 **Interaction mechanism**

The default interaction mechanism for use with the HTC Vive is the controllers that come standard with the system (HTC Corporation 2018). However, the use of these controllers presents two problems in the current context, both stemming from the fact that they are handheld. The first reason this is a problem for the current study is that holding a controller

largely “uses up” a user’s tactile capabilities with that hand, since a large part of the skin of their hand is in contact with the controller itself. The second reason is that holding the controller requires users’ hands to maintain a fixed shape, which limits their ability to explore tactile sensations by, for example, stretching their hand out to interact with an object with their palm. For these reasons, a different device is used as the primary technological mechanism by which interaction takes place: the Leap Motion.



Figure 30: An HTC Vive controller (left) and two HTC Vive base stations (right) (HTC Corporation 2018)

4.1.2.1 Leap Motion

The Leap Motion is a small, commercially available non-contact device that uses infrared (IR) to track the positions of a user’s hands in 3D space without requiring users to hold or wear anything in or on their hands (Weichert et al. 2013; Butt et al. 2017; Leap Motion 2018b). The device is 8cm x 3cm in size (Potter, Araullo & Carter 2013), weighs 45g (Butt et al. 2017), and uses three IR transmitters and two IR depth-cameras to capture the positions and rotations of predefined hand-objects, such as palm, finger, tip, etc. (Weichert et al. 2013; Butt et al. 2017). Additionally, Leap Motion also created an Application Layer Interface (API) allowing for the relatively simple utilisation of the technology inside various development environments, such as Unity and Unreal Engine (Leap Motion 2018a).

Some of the technical details for the device are as follows (Colgan 2014; Butt et al. 2017; Hisham et al. 2017; Parkinson, Zbyszynski & Bernardo 2017):

- **field of view:** approximately 150°
- **frame rate:** approximately 200 frames per second
- **tracking range:** between 25mm and 600mm from the sensor
- **accuracy:** for a setup where the device remains static, tracking is done with an accuracy of approximately 0.2mm, whereas bringing the device itself into motion increased the tracking error to approximately 0.4mm.

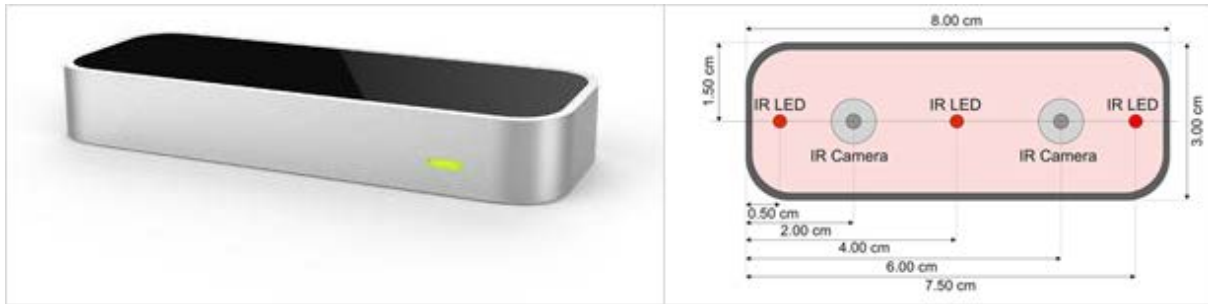


Figure 31: The Leap Motion device (left) (Westover 2013) contains three IR emitters and two IR cameras, as indicated in the diagram (right) (Weichert et al. 2013:1b)

Furthermore, the positions of the hands are tracked relative to the centre of the device itself (Butt et al. 2017), which makes it usable for tracking hands in a VR-setup. The device can be mounted on an HMD and be used to track a user's hands as they interact with virtual objects in front of them, as indicated in Figure 32 below.



Figure 32: The HMD-mounted Leap Motion that was used (left) which allows a user to use their hands to interact with virtual objects in front of them (right) (Lang 2016)

The device, however, is not without its shortcomings. As mentioned, the use of the device while in motion introduces additional, albeit minor, tracking errors (Butt et al. 2017). Additionally, the device also requires line of sight in order to track any hand-object, which means that an obstruction of, for example, a finger behind another hand-object such as a palm prevents the device from being able to track the obstructed hand-object (Butt et al. 2017). Although the field of view is relatively large at 150° (Butt et al. 2017), informal testing for the current study has indicated that users often intuitively attempt to use their hands outside this area. Since the user's physical hand(s) cannot be tracked outside the field of view, the device's API responds to the user moving their hand(s) out of the field of view by destroying the virtual hand object (Leap Motion 2018c), in which case the user cannot use it to interact with other virtual objects until it re-enters the device's field of view.

Nevertheless, the Leap Motion's ability to provide accurate hand-tracking that does not occupy any of the user's tactile faculties presented a significant advantage over the standard Vive controllers for the purposes of the current study. As such, it was used as the main interaction mechanism for the current study. In order to mount the Leap Motion on the Vive headset, a modified version of the official Leap Motion VR Developer Mount (<https://www.thingiverse.com/thing:445866>) was 3D-printed, which was aimed at insulating the HTC Vive headset against heat generated by the Leap Motion device.



Figure 33: The modified version of the official Leap Motion VR Developer Mount that was used

4.1.3 Headphones

Since audio is integral to the current study, high-fidelity audio hardware was required to deliver binaural audio to the user. The headphones used were Audio-Technica ATH-M50X professional monitoring headphones, the details of which are as follows (Audio Technica 2015):

- **weight:** 285g
- **frequency response:** 15 - 28,000 Hz
- noise isolating (closed back).

The weight and noise isolation of the headphones both relate to the “inclusive” aspect of immersion (Slater & Wilbur 1997; Slater 2003), while the frequency response relates to the “vividness” aspect (Regenbrecht, Schubert & Friedmann 1998) and was also crucial in order to ensure adequate sound quality for the audio component of the system.

Having established all the significant hardware components of the overall system, the following section discusses all matters related to the software implementation of the prototype.

4.2 *Software implementation*

Since the usability test focused on the prototype for the purposes of inducing intersensory illusions, this section includes all matters regarding specific implementation choices as well as broader software implementation concerns. These broader concerns are discussed first.

4.2.1 *Software development environment*

The Unity game engine, sometimes called Unity 3D (Bartneck et al. 2015), is a freely available game development engine that allows for the creation of a variety of interactive software, such as games, simulations, and visualisations in 2D and 3D (Kim et al. 2014; Bartneck et al. 2015; Broderick, Duggan & Redfern 2017; Unity Technologies 2018a). The use of Unity offers several advantages during development, such as:

- an included toolset for development (Kim et al. 2014)
- the ability to test and adjust on the fly, which significantly speeds up testing iterations (Kim et al. 2014)
- a modular extendable development environment (Bartneck et al. 2015; Broderick, Duggan & Redfern 2017)
- a large development community (Broderick, Duggan & Redfern 2017)
- a flexible scripting environment that allows the use of existing well-known programming languages such as C# and JavaScript (Broderick, Duggan & Redfern 2017)
- built-in support for various VR-platforms such as HTC Vive and Oculus Rift (Unity Technologies 2018b).

However, the largest advantage of using Unity is the streamlining of development, allowing the developer, i.e. the researcher, to focus on the implementation of high-level study-related issues, such as audio and user-interaction, without having to focus on other issues such as 3D graphical rendering and physics-implementations (Broderick, Duggan & Redfern 2017).

Additionally, two Unity plugins were used to streamline development: the SteamVR plugin, which communicates with and manages the HMD itself (Valve Software 2018), and the Leap Motion core plugin, which communicates with the Leap Motion device to create and manage the virtual hands (Leap Motion 2018c).

For delivering binaural audio, Google Resonance Audio was used (Google 2018b). Resonance Audio is a “multi-platform spatial audio SDK” (Google 2018b), which simulates a number of qualities in order to deliver binaural audio, such as interaural time differences (ITDs), interaural level differences (ILDs), head-related transfer functions (HRTFs), as well as reverb for simulating room acoustics (Google 2018c). Resonance Audio is available as a Unity plugin (Google 2018d), which is the version that was used.

With the broad software concerns having been dealt with, the next section discusses all matters regarding the implementation of the prototype that was used in the usability tests.

4.2.2 Software prototype details

Before discussing the details regarding the software prototype, it is worth revisiting some of the goals and constraints established in previous sections, the first, and most obvious, being what the prototype should accomplish and the constraints of this goal.

4.2.2.1 Goals and constraints

As discussed in section 2.6, the broad aim of the prototype was to induce illusory tactile feedback by means of intersensory illusions using binaural audio. Some of the details regarding the mapping between audio and tactile feedback were discussed in section 2.5.5, which formed the basis of the design of the mechanisms aimed at accomplishing this broad aim. It is worth noting, however, that neither of the aforementioned sections made any attempts at integrating these various phenomena or offering an encompassing solution to create intuitive mappings between audio and tactile feedback. Instead, the current study took a modular approach with regards to designing interactions that aimed to induce the desired effect in a user. What this means is that instead of a single implementation, the prototype included a variety of different implementations of interactive audio sources, each of which took a different approach to attempt to induce intersensory illusions.

In order to present a variety of different possible solutions to the user, the analogy of different rooms was selected as an overall structure for the various implementations. The prototype was thus divided into several virtual rooms, with each room dedicated to a specific purpose. (For the sake of brevity, it can be assumed without being stated that any objects or environments that form part of the software prototype, i.e. the VE, were virtual objects, such as virtual rooms, virtual blocks, etc.)

Apart from being an intuitive way to structure various pieces of VR-content, the use of rooms offered two additional advantages:

- It separated any visual or audio content between different implementations, preventing the user from being distracted by the contents of adjacent implementations.
- Each room could be numbered and colour-coded to aid the user in recalling their experience from one implementation over another.

Users were able to move between rooms by interacting with designated objects that served this specific purpose. This “movement” took the form of instantaneous transportation to a different point in 3D virtual space, in other words, interacting with one of these objects “teleported” the user to a different room. Interacting with a teleportation object, which, in the prototype, took the form of a hovering ball, also triggered a sound cue to signal teleportation between rooms, thus providing feedback that the participant has successfully taken an action (Preece, Sharp & Rogers 2015:1). Apart from providing an intuitive way to move between virtual rooms, this interaction mechanism also addressed a previously-addressed constraint: motion sickness. As discussed in section 2.2.3, motion sickness is generally ascribed to a false perception of self-motion due to visual or audio stimuli while the body is stationary (Curtis 2014). As such, it results from the mismapping between the perceptions resulting from different sensory faculties, for example, if a person perceives their virtual-self as being in motion while their physical body is stationary (Bos, Bles & Groen 2008; Curtis 2014). The teleportation mechanism prevented this issue by preventing any form of mismatched movement between the user’s virtual body and their physical body:

- Users were allowed (minimal) movement inside the play area, during which virtual movement corresponded very close to 1:1 with physical movement due to the Vive’s high accuracy and low latency (Niehorster, Li & Lappe 2017; HTC Corporation 2018).
- The movement of larger distances between rooms involved instantaneous travel from one point in virtual 3D space to another, during which the user did not perceive any movement of their virtual body.

This teleporting mechanism eliminated the need for any significant movement from the user and, as such, the prototype was designed for a user in a seated position. Thus, very little overall movement was required from the user when interacting with the prototype and any unnecessary virtual locomotion during the usability was strictly avoided, thus minimising visually-induced motion sickness during the usability test.

Another constraint regarding the design of the prototype relates to the degree of objectivity attainable during the usability test itself, including the observation thereof as discussed in section 3.4.2. Since the current study was qualitative, complete objectivity was assumed to be impossible to attain (Pickard 2013:1); instead the focus was on minimising the influence the researcher had on the experiences of participants during the test in order to maximise the transferability of findings (Morgan, Krueger & King 1998:6; Pickard 2013:1). Furthermore, any form of interaction between the researcher and participant was expected to have negative effects on the levels of presence experienced by the participant during the test (Slater & Wilbur 1997).

Thus, in order to minimise the influence of the researcher, maintain high levels of presence, and conduct effective non-participant observation (Preece, Sharp & Rogers 2015:7), the prototype was designed in such a way as to require no involvement from the researcher once the usability test has started, or, at the very least, minimal involvement. In order to accomplish this, three guiding factors were used to design the prototype:

- Users were given instructions inside the VE. The fact that instructions were given inside the VE, as opposed to before the test, is important, since it focused the user's attention on stimuli in the form of instructions inside the VE, which was expected to have a positive effect on involvement (Witmer & Singer 1998; Lessiter et al. 2001). It was also expected that some users might have difficulty remembering instructions, which would otherwise require them to "exit" the VE in order to refresh their memories, thus negatively affecting presence (Slater & Wilbur 1997). Instructions included text- and graphical-elements to aid understanding.
- Although instructions were given, the tasks that participants were required to perform were kept as simple as possible, in order to minimise possible confusion.
- Where possible, affordances were used in the design of virtual objects for interaction. Affordances refer to the perceived usability of objects that result from their physical design, for example, a button "affords" pushing due to its physical design (Preece, Sharp & Rogers 2015:1).

In addition to these guiding factors, that are more specific to the current prototype, a number of heuristics were employed as a quality assurance measure with regards to prototype's design.

4.2.2.2 Design heuristics

In the current context, heuristics refer to rules/guidelines that a software system could be tested against by one or more usability experts in a process known as a heuristic evaluation or

expert review (Nielsen & Molich 1990; Barnum 2010:3). However, for the current study, heuristics were used as a quality control measure during development in order to ensure the usability and high levels of immersion of the system. A number of established usability heuristics exist, such as those put forth by Nielsen and Molich (1990), which are aimed at evaluating traditional desktop environments (Nielsen & Molich 1990). However, these desktop-oriented heuristics are unfit for VEs, due to their inherently different ways of interacting with the system and the fact that VEs contain interaction paradigms not found in desktop paradigms, such as movement and orientation (Sutcliffe & Kaur 2000).

The current study used a specialised set of heuristics put forth by Sutcliffe and Gault (2004), derived from those put forth by Nielsen and Molich (1990), which are as follows (Sutcliffe & Gault 2004):

1. **“Natural engagement:** Interaction should approach the user’s expectation of interaction in the real world as far as possible. Ideally, the user should be unaware that the reality is virtual. Interpreting this heuristic will depend on the naturalness requirement and the user’s sense of presence and engagement.
2. **Compatibility with the user’s task and domain:** The VE and behaviour of objects should correspond as closely as possible to the user’s expectation of real-world objects; their behaviour; and affordances for task action.
3. **Natural expression of action:** The representation of the self/presence in the VE should allow the user to act and explore in a natural manner and not restrict normal physical actions. This design quality may be limited by the available devices. If haptic feedback is absent, natural expression inevitably suffers.
4. **Close coordination of action and representation:** The representation of the self/presence and behaviour manifest in the VE should be faithful to the user’s actions. Response time between user movement and update of the VE display should be less than 200 ms to avoid motion sickness problems.
5. **Realistic feedback:** The effect of the user’s actions on virtual world objects should be immediately visible and conform to the laws of physics and the user’s perceptual expectations.
6. **Faithful viewpoints:** The visual representation of the virtual world should map to the user’s normal perception, and the viewpoint change by head movement should be rendered without delay.
7. **Navigation and orientation support:** The users should always be able to find where they are in the VE and return to known, pre-set positions. Unnatural actions such as

fly-through surfaces may help but these have to be judged in a trade-off with naturalness (see heuristics 1 and 2).

8. **Clear entry and exit points:** The means of entering and exiting from a virtual world should be clearly communicated.
9. **Consistent departures:** When design compromises are used they should be consistent and clearly marked, e.g. cross-modal substitution and power actions for navigation.
10. **Support for learning:** Active objects should be cued and if necessary explain themselves to promote learning of VEs.
11. **Clear turn-taking:** Where system initiative is used it should be clearly signalled and conventions established for turn-taking.
12. **Sense of presence:** The user's perception of engagement and being in a 'real' world should be as natural as possible."

It should be noted that there were two driving factors behind the formulation of these heuristics that were purposefully formulated to differentiate these heuristics from the traditional desktop-based heuristics (Sutcliffe & Gault 2004). These were the following two factors (Sutcliffe & Gault 2004):

- VR's tendency toward intuitive interaction, rather than traditional mouse-and-keyboard approaches
- the importance of immersion in experiencing VR.

This focus on intuitive interaction and immersion (as well as presence in the heuristics themselves) kept the aforementioned heuristics as relevant for the current study as they were when they were formulated and also aligns the goal of the aforementioned set of heuristics with the focus of the current study (Sutcliffe & Gault 2004). Further similarities of focus can be found in the "consistent departures" heuristic, with its mention of "cross-modal substitution" as well as the authors' elaboration of this heuristic, stating that it "draws attention to the problem of using visual and audio feedback as a substitute for the sense of touch" (Sutcliffe & Gault 2004). However, number 11 ("clear turn-taking") was not relevant in the context of this study, as the current study did not require any form of (autonomous) initiative from the system, nor from other VR-users.

These heuristics, specifically number 1 – 5, at first appear to work on the underlying assumption that, for the most part, VEs are trying to emulate the real world as realistically as possible, the details and pitfalls of which have been previously addressed in section 2.3.1.2. However, the authors do extend the heuristics to "unnatural" worlds (VEs with no counterpart in reality), which requires that the evaluator's notion of "naturalness" lay

between said “unnatural” world and the “user’s model of the task and domain” (Sutcliffe & Gault 2004).

The structure of the aforementioned heuristic evaluation is mostly similar to that of Nielsen and Molich (1990), but with two notable differences: the tasks to be completed and the “technology audit” (Sutcliffe & Gault 2004). First, since VEs are assumed by the authors, for the most part, to emulate the real world, the authors suggest that the tasks that are carried out during the evaluation should be similar to real-world tasks (Sutcliffe & Gault 2004). This can be compared with the notion of “matching/interactivity” as an aspect of immersion, as discussed in section 2.3.1.2, which again aligned the heuristics with the current study. Using the concept of “matching/interactivity” instead does not require that the tasks to be performed have an exact real-world equivalent, but rather that they conform to the user’s internal representation systems to appear as “natural” interactions.

The second notable difference is what the authors call a “technology audit”, which involves discussing the presence/absence of features across certain categories that the system may or may not contain to establish a baseline of what the system is capable of (Sutcliffe & Gault 2004). These categories are (Sutcliffe & Gault 2004):

- **Operation of the user’s presence:** how the user is represented and controlled inside VR. The authors refer to the representation of the user’s virtual hands, body, etc. as the user’s “presence”, although the current study has already established the concept of egocentric virtual body representation to refer to this notion (as discussed in section 2.3.1.2).
- **Lack of haptic feedback:** refers to the lack of haptic feedback in most VEs. Although significant development has been done in this area since, the lack of haptic feedback is still a relevant concern in VR (as discussed in section 2.4.2.2).
- **Interactive techniques:** how users interact with and navigate their environment.
- **Realistic graphics:** emphasises the importance of detailed graphical displays, especially when operating in visually complex environments. In the current study, this fell under vividness, which does not require “realistic” graphics as necessarily having a real-world counterpart, but rather high fidelity in the visual channel, as well as in other channels.

Although there have been many advancements in the field of VR technologies, especially since the recent “resurgence” (see section 2.1.2.2), the current study still considers the technology audit a useful tool, as it establishes a frame of reference against which to evaluate the performance of the system (Sutcliffe & Gault 2004). Additionally, the authors also list

classes of design features, which are meant to be used alongside the heuristics when identifying problems, which are as follows (Sutcliffe & Gault 2004):

- **Graphics display**, 3D depth or perspective distortion, poor resolution of image. Indicated by perceptual difficulties.
- Moving and manipulating the **user presence**, sub-divided into the hardware device(s) being used (e.g. glove, joystick, 3D mouse, etc.) and the representation of the user in the VE. Indicated by navigation and manipulation difficulties. As discussed above under “*Operation of the user’s presence*”, since the notion of an egocentric virtual body representation has already been established to refer to the user’s virtual representation, the current study uses this term instead.
- Interaction with **objects and tools** in the VE. Indicated by unsuccessful attempts to act; or poor feedback misleads users.
- **Environmental features**. Parts of the environment which created unexpected effects such as moving through walls and floating objects.
- **Interaction with other controls**, such as floating menus and palettes.
- Other **hardware problems**, such as with head-mounted displays (HMD) and shutter glasses.

Since the current study did not make use of a formal heuristic evaluation, the 12 heuristics and the accompanying design features were not formally addressed but are rather used as a set of design guidelines during development. However, since the current study does still value the technology audit, each of the four points are discussed here in turn:

- **Operation of the user’s presence:** the user was not represented with a full virtual body but was only able to see themselves by means of their virtual hands, which were controlled by the Leap Motion device.
- **Lack of haptic feedback:** since the Leap Motion is a hands-free device, there was no haptic feedback, apart from the (desired) illusory feedback induced by visual and audio feedback.
- **Interactive techniques:** the two main hardware systems, i.e. the HTC Vive and the Leap Motion, were used to offer all interaction mechanisms, specifically the head tracking, which was controlled by the HTC Vive, and hand tracking, controlled by the Leap Motion.
- **Realistic graphics:** since the current experiment did intend to emulate reality to a degree, as opposed to emulating some sort of fictional reality, the graphics were intended to be suitably realistic for this purpose, an example of which can be seen in Figure 36. However, with regards to the realism of the hand models controlled by the

user via the Leap Motion, the current study did not aim to create completely realistic-looking hands, in order to avoid the undesirable phenomenon known as the uncanny valley. The uncanny valley describes an area on the spectrum between human unlikeness and likeness in which an object closely resembles real human anatomy, but is dissimilar enough to create an unsettling effect for most people, as illustrated in Figure 34 (Mori 1970; Złotowski et al. 2018). This unsettling effect was originally predicted to be amplified for objects that aim to move in a human-like fashion (Mori 1970), although this prediction is contested (Piwek, McKay & Pollick 2014), and may result from the attempt to model any number of human body parts, such as the face and hands (Mori 1970; Poliakoff et al. 2013). As such, to prevent this possible unsettlement, the current study used purposefully abstract hand-models that functionally resemble real hands enough to be easily recognisable as such, but did not attempt to realistically model human anatomy, as indicated in Figure 35 (Mori 1970; Poliakoff et al. 2013).

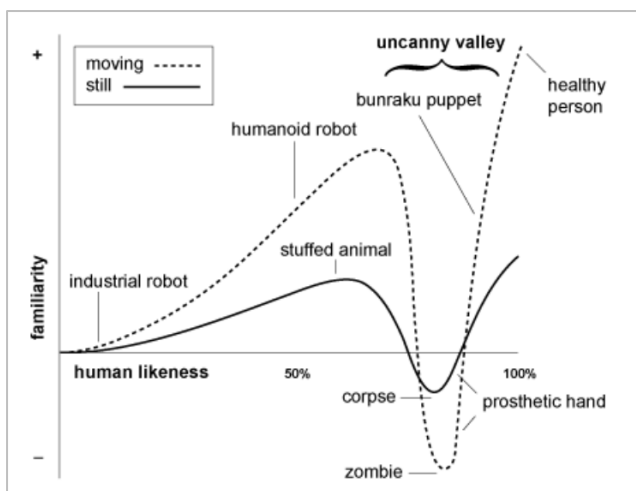


Figure 34: A simplified representation of the uncanny valley (Mori 1970:1)



Figure 35: The model of the left hand that was used to represent the user's hands in the VE. The front of the hand is shown on the left and the back on the right

The next section discusses in more detail how these methods and heuristics were implemented by discussing the structure and details of the prototype.

4.2.2.3 Structure of the prototype

As mentioned in section 4.2.2.1, the prototype was divided into several virtual rooms, each of which was aimed at a specific purpose. The first room served a special purpose, whereas the rest were variations of the main purpose of the prototype. As such, the first room, heretofore referred to as the “introductory room”, is discussed first.



Figure 36: The introductory room

4.2.2.3.1 Introductory room

The purpose of the introductory room was to acquaint users with the VE. This was especially important for users who have had little to no VR- or gaming-experience, as the experience could be completely novel and possibly startling for them. Thus, the introductory room did not, strictly speaking, form part of the usability test, but was used instead to acclimatise users (to “calibrate” them, in a sense) to the VE before the test begins (Rubin & Chisnell 2008:9). The introductory room consisted of a simple desk with stacks of blocks with which the user could interact using their hands. Users were also encouraged, via text- and visual-instructions, to interact with the blocks in order to get them comfortable with using their hands for interaction.

Additionally, the room contained a clock which was situated to the left of the user’s starting position and produced realistic ticking sounds. The reason for this was to introduce the user

to binaural audio in a natural way by providing a sound source outside their field of vision which, as the user turned their head to find the source of the audio, changed due to HRTFs (Wanrooij & Opstal 2007), thus introducing the user to localisable audio without explicitly stating this feature. In order to make the room seem more natural, a room tone was recorded in the same location and conditions, in other words, with the same background noise, in which the usability test took place. The room tone was recorded with a Zoom H2n (Zoom 2013) and was played back on repeat in the introductory room as well as in every other room in the prototype. The introductory room also explained the workings of the teleportation mechanics to the user via text- and visual-instructions, which they could use to progress to the next room when they were done acclimatising. The layout of the introductory room is illustrated in Figure 37 below.

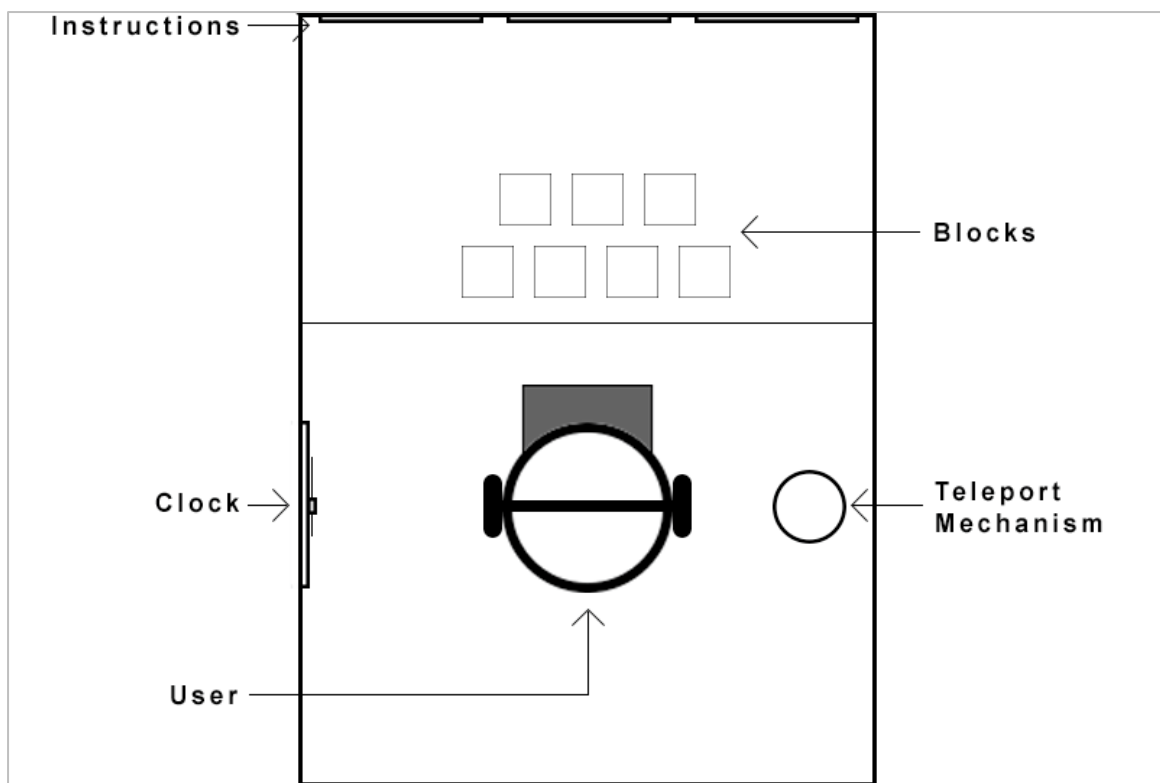


Figure 37: A top-down diagram of the introductory room

4.2.2.3.2 Experiment rooms

With the exception of the introductory room, each room in the prototype followed a similar structure. For the sake of recall, each room used a unique colour for the walls and was given a number, which was easily visible to the user. Rooms also contained instructions in the form of text and graphics. The same teleportation mechanisms were used for the main rooms as was used for the introductory room, allowing the user to travel back and forth between all rooms in the prototype. Each room contained two to four blocks, which are referred to as

“tactile blocks” from this point onwards. A tactile block formed the basis of a single possible implementation of a strategy for inducing illusory tactile feedback. The block itself was rectangular with an optional texture on the top side of the block, depending on the implementation strategy as well as the room the block was in, as illustrated in Figure 39 below. The blocks were positioned in such a way that the user could comfortably reach all of them with their hands without having to move in the virtual space.

Interaction with a tactile block took the form of a rubbing action. This meant that when a user “touched” the block and moved their hand around, this action produced a sound. In order to make this interaction natural to the user, the volume of the sound produced correlated with the velocity of the hand that was “rubbing” the block. Furthermore, the vertical displacement of the block, i.e. the “pressure” induced by the user’s hand, also positively correlated with volume as well as other possible factors, which are discussed below in section 4.2.2.4. In order to utilise the capabilities of binaural audio, the sound source was always localised to the position of the user’s hand that was rubbing the block, the goal being that the sound always seemed to be originating directly from the user’s interaction with the block.

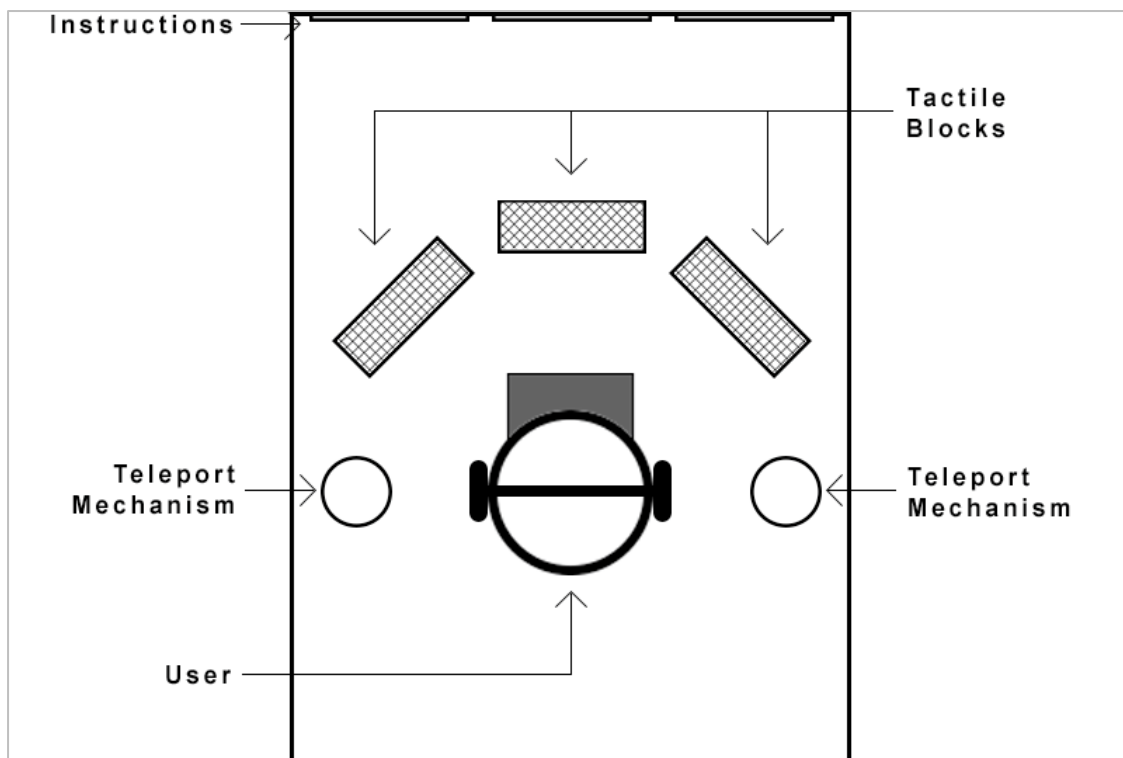


Figure 38: A top-down diagram of the experiment rooms

Another important issue regarding the tactile blocks was their physical response to the user’s interaction with them. Since the Leap Motion is not a kinaesthetic feedback device, it does not

offer force-feedback preventing the user's hand from moving through virtual objects in the way, for example, the *PHANToM* device does (Salisbury & Srinivasan 1997). This presented a problem with regards to the intended tactile interaction: a user's virtual hand, when rubbing a virtual block, would easily go through the block. The reason this was a problem is that it visually contradicted the analogy of rubbing a block, since rubbing an object involves gliding one's hand across the surface. In fact, when rubbing an object, it is exactly this interaction between the person's skin and the surface of the object which causes the sensation. Thus, contradicting this interaction visually was expected to have a negative effect on the believability of the rubbing interaction, since users could no longer rely on their tacit knowledge of how rubbing an object works and feels.

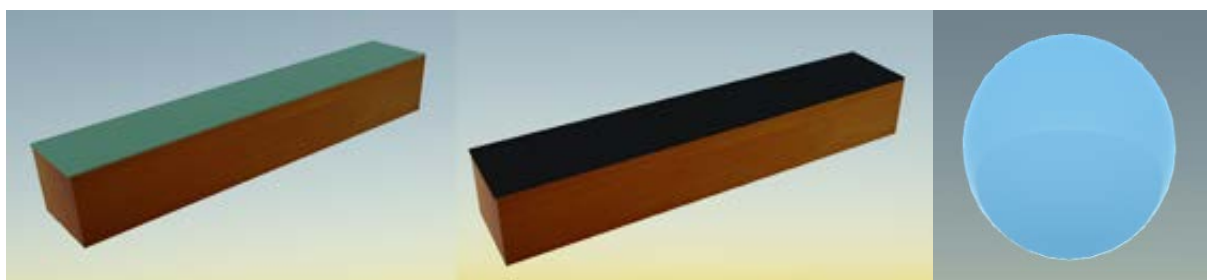


Figure 39: An un-textured (coloured) block on the left, a sandpaper-textured block in the middle, and a teleportation mechanism (teleportation ball) on the right

The solution to this problem, for the purposes of the current study, was to invoke a spring-loaded analogy for the blocks. Instead of being fixed to a point in space, blocks were suspended in a point in space until a user pressed down on them. Pressing down on a block pushed that block down, as illustrated in Figure 40 below, until the “pressure” was released, at which point the block returned to its original position. The movement of blocks was limited to moving up and down, not allowing for any other movement or rotation. This created a mechanism akin to having the objects suspended via an invisible spring, which contracted and then expanded in response to interaction with the user's hands. Blocks were given enough spring-loaded flexibility to be displaced as far as the user was expected to be able to reach, thus preventing the user's hand from ever going through the block. A side-effect of this solution was the possibility of users experiencing a sense of illusory kinaesthetic feedback, similar to that which is experienced when a visual virtual spring is used to indicate a physical force (Biocca, Kim & Choi 2001; Biocca et al. 2002). However, the current study embraced this side-effect by using this sense of “pressure” as a parameter which influenced the playback and qualities of the audio feedback used.

The next section discusses the main strategies for using audio feedback and how this feedback reacted to the user's hand movements.

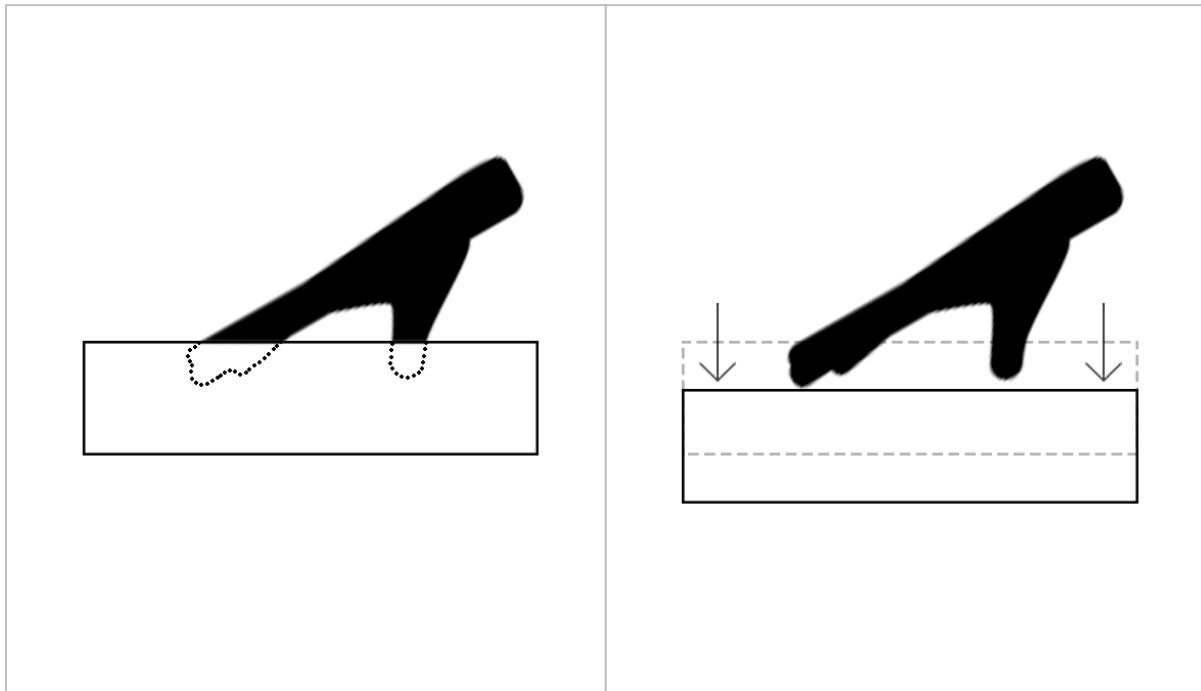


Figure 40: A fixed block allows a user's virtual hand to go through the block (left), while the spring-loaded block is displaced by the user's hand (right)

4.2.2.4 Strategies for inducing illusory tactile feedback

In order to induce illusory tactile feedback, the current study made use of three different main strategies in which audio was played and affected by the user's hand movement and interaction with the tactile block. Each one of these strategies are discussed separately, but were often used in combination with one another, as discussed in section 4.2.2.6.

4.2.2.4.1 "Pure texture" strategy

The first strategy, which was also the simplest, was to play recordings of real textured objects being stroked as the basis for inducing the sensation of texture. For the purposes of the current study, two objects were chosen as the basis for textural sounds: a sheet of sandpaper and a woollen jersey. These objects were chosen, since both of them were believed to be very recognisable textures and thus to produce recognisable textural sounds. These objects are also associated with contrasting textures: rough/grainy vs. soft/smooth (Tjadura-Jiménez et al. 2014) and are thus easily distinguishable. The sounds to be used were recorded using a Line Audio CM3 microphone and were produced by rubbing one hand against the object in a slow and continuous fashion, as indicated in Figure 41, thus giving it the ability to be looped indefinitely. The audio recordings were also normalised to -0.1db for consistency between audio recordings and converted to monophonic audio files using Adobe Audition CC 2015 (Adobe Systems Software 2018) as the virtual spatial audio created by Google Resonance works best with monophonic audio files (Google 2018a).



Figure 41: The process of recording the textural sound sources

The aim of the way the recording was utilised in the “pure texture” strategy was to emulate interaction with a real textured object. To accomplish this, the tactile block was given an associated recording (from one of the aforementioned recordings), which was played continuously, but muted programmatically. Only when the block was displaced, i.e. when the user rubbed the block, was the recording unmuted, in which case the volume positively correlated with both the user’s hand-velocity and the amount the block was displaced. The desired effect of this was that the act of rubbing a tactile block created audio feedback that behaves similar to that resulting from rubbing a real object.

For all tactile block strategies, the volume of the audio being played was calculated as follows:

$$\text{blockDisplacement} = |\text{startingBlockPositionY} - \text{currentBlockPositionY}|$$

$$\text{handVelocity} = \sqrt{\text{handVelocityX}^2 + \text{handVelocityZ}^2}$$

$$\text{audioVolume} = (\text{handVelocity} / \text{expectedMaxHandVelocity}) \times \text{blockDisplacement} \times \text{conversionConstant}$$

For the current purposes, the X-, Y-, and Z-axis were defined as being relative to the observer’s, i.e. participant’s, point of view. Thus, the Y-axis was defined as vertical distance, the X-axis as horizontal distance, and the Z-axis as depth, as indicated below in Figure 42.

It should be noted that the calculation of the block’s displacement using an absolute value allowed it to calculate the audio volume while being pushed bi-directionally on the Y-axis, i.e. both down and up. The hand’s velocity was calculated as the hypotenuse to the hand’s X- and

Z-velocity and was divided by the maximum speed that the user's hand was expected to move at during the test (which was determined during informal testing by the researcher). This gave a value from 0 to 1 which was multiplied by the block's displacement and a conversion constant, which was an engine-specific value modified in order to give a natural-sounding volume. This conversion constant was also determined by the researcher during informal testing.

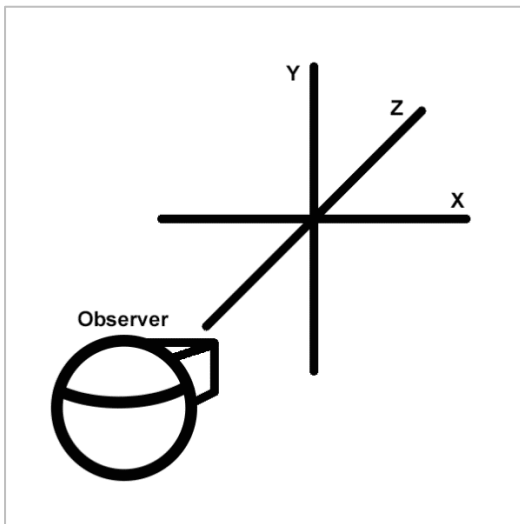


Figure 42: The X-, Y-, and Z-axis relative to the observer

4.2.2.4.2 Atonal abstract strategy

The other two strategies did not rely on real recordings of audio, but instead on synthesised audio. The basis for both of these was the use of synthesised musical notes that were made with four of the most mathematically simple and commonly used waveform shapes in sound synthesis: squarewave, sawtooth, triangle, and sinewave (Lane et al. 1997; Välimäki & Huovilainen 2006), which are illustrated in Figure 43. For both abstract strategies, a series of chromatically-separated notes that span four octaves using each of these four waveforms were created using Propellerhead Reason 5 (<https://www.propellerheads.se/en/reason>).

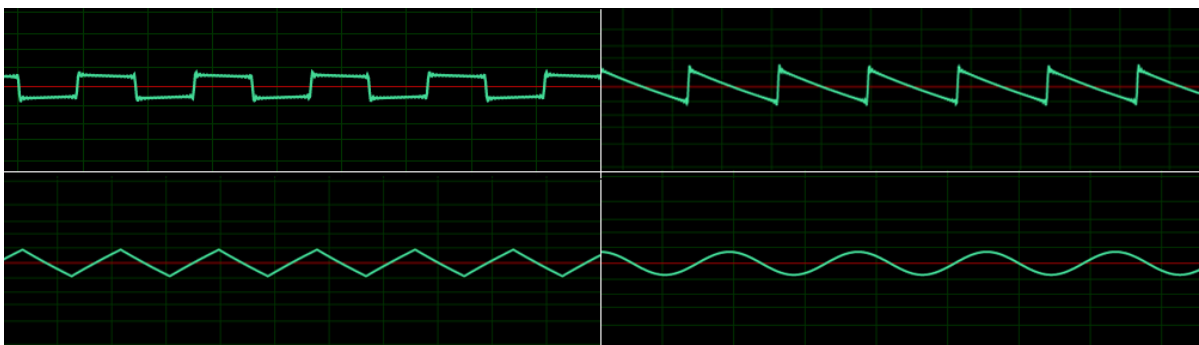


Figure 43: From left to right and top to bottom: the same note created with a squarewave, sawtooth, triangle, and sinewave

Using these musical notes, the first abstract audio strategy continuously played a single of these notes but muted it programmatically unless the user was rubbing the block, similar to the “pure texture” strategy. The volume was also controlled by the user’s hand velocity and the displacement of the block, but the note was pitch-bent upwards while the user was moving their hand. The amount of pitch-bending was controlled by the user’s hand velocity while the pitch-bending range was controlled by the amount of displacement of the block. The intent of this mapping between the hand velocity and pitch-bending amount was to abstractly emulate the interaction between a person’s hand and the textural qualities of an object, such as jagged or uneven edges, with the increase and decrease in sound frequency matching the increase and decrease of collision of one’s hand with these qualities, similar to the “rhythmic” mapping between audio and tactile (Hoggan & Brewster 2006a; Hoggan & Brewster 2006b; Hoggan & Brewster 2007). The mapping between the block’s displacement and pitch-bending range was meant to further emulate pressure by emulating the effects of an increased physical force applied to the block’s surface.

Using this strategy, a number of parameters could be controlled for each tactile block, as found in other cross-modal studies (Hoggan & Brewster 2007; Eitan & Rothschild 2011), which included the following:

- **The timbral qualities of the audio:** by selecting different waveforms. The four waveforms can be divided into rough sounds (sawtooth and squarewave) and smoother sounds (sinewave and triangle).
- **The pitch:** by changing the base frequency, and subsequently all other frequencies, of the pitch-bending note.
- **The amplitude:** by modifying the amount that hand velocity affects amplitude.
- **The spatial location:** by changing the position of the tactile block relative to the observer.

However, since the focus of the current study was on attempting to induce illusory haptic feedback and not on a broad experimental approach to test a range of cross-modal information mappings, the number of parameters was purposefully kept to a minimum. As such, pitch and amplitude were not modified across tactile blocks and spatial location was only modified insofar as that blocks were placed around a user for practical reasons. All tactile blocks using the atonal abstract strategy thus made use of the same musical note as the starting note. The prototype used C two octaves below middle C as the starting note, as informal testing has shown this note to be easily audible across all four waveforms.

The amount of pitch-bending was calculated as follows:

$$\text{pitchBendAmount} = \text{handVelocity} / \text{expectedMaxHandVelocity}$$

The hand's velocity was calculated the same way as for the pure texture strategy, which again gave a value between 0 and 1, which was chosen due to the numerical values for the amount of pitch-bending used by Unity and informal testing by the researcher indicated this range to resemble a type of tactile interaction.

4.2.2.4.3 Tonal abstract strategy

The third strategy for presenting and modifying audio also relied on the aforementioned series of musical notes created, but, whereas the previous strategy did not make use of their musical properties and only relied on their continuously changing pitch, the third strategy used them as discrete notes in a musical scale. As mentioned above, a series of chromatically-separated notes were created over four octaves. This allowed for the implementation of musically-based note sequences that were played in reaction to the user's hand movement. Similar to the previous two strategies, hand-velocity and block-displacement controlled volume. However, whereas the atonal abstract strategy only made use of one note which was played continuously, the current strategy played a randomised sequence of notes, with an increase in the user's hand-velocity correlating to an increase in the rate at which notes were played and a decrease in their duration and the block's displacement controlling the octave-range from which potential notes were randomly selected.

The length of audio notes and the range from which notes were selected were calculated as follows:

$$\text{audioLength} = (1 / \text{handVelocity}) * \text{lengthConstant}$$

$$\text{noteRange} = \min\{\text{round}(1 / \text{currentBlockPositionY} * \text{positionConstant}), \text{maxOctaveRange}\}$$

Both constants refer to values chosen by the researcher during informal testing to resolve engine-specific numerical values to specific ranges. The length constant was selected to map the lengths of audio notes being played to values that make individual notes discernible without sounding distinctly musical. The position constant was selected to map a displacement of the block near the maximum expected displacement to a note range of the maximum number of octaves (which, as discussed above, was four), thus utilising the full range of notes in the four-octave range while limiting it to this note range.

The note to be played was randomly selected as follows:

```
randomNote = RandomNumber{0, scaleLength}
```

```
randomOctave = RandomNumber{0, noteRange}
```

```
noteToBePlayed = allNotes[scale[randomNote] + (randomOctaves * 12)]
```

First, a random note was chosen in one octave of the scale, then the number of octaves above the starting octave was randomly chosen using the *noteRange* value calculated above. These two randomly chosen values were then used to select one note from the list of all notes that were created, for example, the 5th note of the major scale 2 octaves above the starting octave would give the 31st note, assuming that counting starts at 0.

The intent with this strategy was also to abstractly emulate the interaction between a person's hand and a physical object, but instead of mimicking the presence of textural qualities of an object with changes in a continuous sound, these qualities were mimicked using short, individually-played sounds. The desired effect of this strategy was to create the impression of a large number of small textural details in a virtual object by producing a large number of short pieces of audio. The musical notes were also randomised, since using an existing musical sequence, such as an ascending musical scale, was predicted to seem unnatural and to draw undesired attention to the specific notes that were being played. As with the previous two strategies, the intent of the mapping regarding the block displacement was to create the impression of physical pressure.

Using this strategy, the general parameters that could be controlled for each tactile block were largely similar to that of the previous strategy, with the exception of pitch. Since the notes were played in a randomised sequence, the resulting pitch could only be controlled indirectly, since increasing the note range from which notes were selected increased the average pitch of the sounds played. Furthermore, using musical notes instead of atonal pieces of audio allowed for the use of existing musical structures, such as scales. This allowed for each tactile block to be associated with a different musical scale and use this scale to randomly select notes from. However, the effect of different musical scales on the perception on illusory tactile feedback was not explored as part of the current study and a single musical scale, the chromatic scale, was used for all tactile blocks using the tonal abstract strategy. The chromatic scale was selected in order to avoid associations that users might have with more commonly used scales, such as associations between major/minor and happy/sad (Crowder 1985).

Having established the three main strategies that were used and combined across various tactile blocks in various virtual rooms, the next section explores an audio effect that was

expected to have the potential to enhance the cross-modal capabilities across all these strategies.

4.2.2.5 Proximity effect

As discussed in section 2.5.5.3, the “proximity effect” of the audio feedback can potentially be used to enhance the perceived “intimacy” of a sound source by perceptually “internalising” the audio source to a degree (Brungart 2002; Phillips 2015). Although Google Resonance does include functionality for adding near-field effects to an audio source, at the time of writing, this only resulted in an increase in volume for virtual sound sources that are located less than one (virtual) meter away from the listener (Resonance Audio 2018). Thus, added measures were taken to further emulate the proximity effect by increasing the volume of the recorded audio around 500Hz by 6 decibels using Adobe Audition (Brungart 2002; Schneider 2010; Clifford & Reiss 2011; Neumann 2018). The same was not done for the abstract audio notes, since participants were not expected to have a reference point to compare these types of sound to, as they do not appear as a reaction to tactile interactions the same way the recorded audio does.

Having discussed the broad implementation strategies for inducing illusory tactile feedback, the next section discusses how these strategies were used by discussing the detailed layout of the prototype in terms of its virtual rooms and what each contained.

4.2.2.6 Detailed prototype layout

This section discusses the layout of the prototype in terms of the specific tactile block implementations that were used in each virtual room. Each room is discussed separately along with the details of the tactile blocks that each contained.

As the introductory room has already been discussed, it is omitted from the current section.

Room 1

The first room contained two tactile blocks, both of which used the pure texture strategy. The goal of this room, apart from giving participants opportunity to interact with the pure texture strategy, was to ease participants into the structure of the rest of the prototype and offer them an opportunity to interact with the tactile blocks without overwhelming them with choices. The first block to the left of the participant used the sandpaper-audio and the block on the right used the wool-audio. Both blocks were visually textured so as to look like their corresponding textures as indicated in Figure 44. The first room was the only room that used textured blocks; every other room used a smooth texture and the same colour as the walls for the tactile blocks. The reason for this was to first introduce the participant to the notion of the

textured blocks by visually indicating them as having specific textures and then to neutralise their visual appearance for the rest of the prototype in order to minimise the potential effect the visual textures might have on the perceived textures.

For the sake of brevity, the remainder of this section uses a table format to describe the contents of each room in terms of the tactile blocks that it contained. Each tactile block is listed, starting from the left and progressing clockwise (refer to Figure 38 for a general layout of the main rooms) and the implementation strategy used for that tactile block is listed in table form.

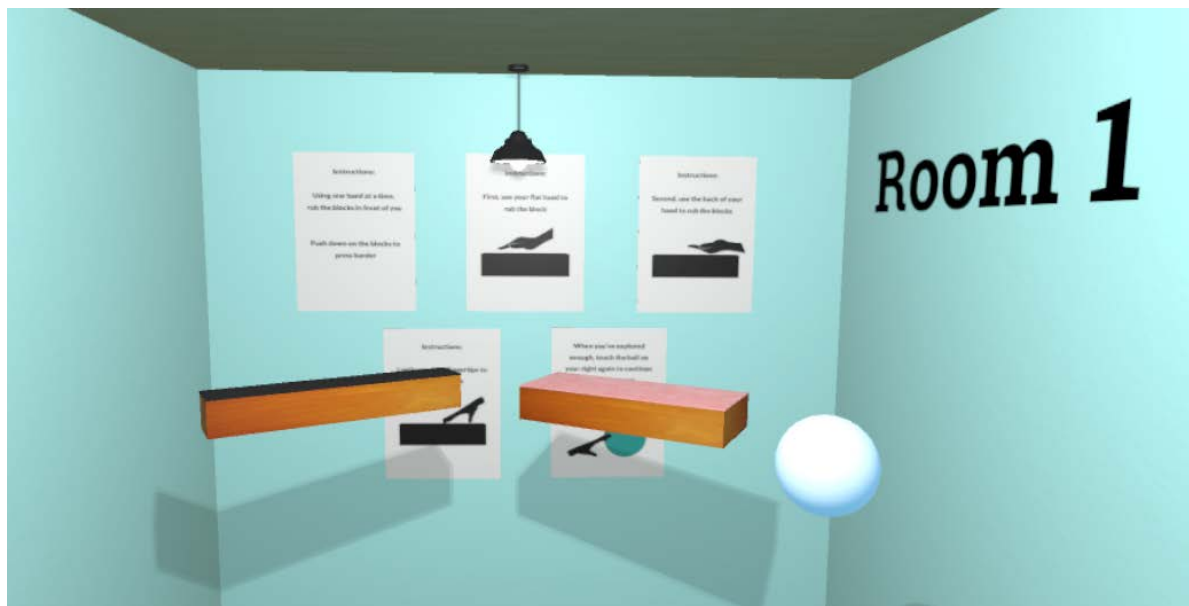


Figure 44: A screenshot of room 1. The user is located so as to easily be able to reach both blocks and the teleportation sphere

Room 2

Block 1	Atonal abstract: sawtooth
Block 2	Atonal abstract: triangle
Block 3	Atonal abstract: sinewave

The purpose of room 2 was to introduce participants to the atonal abstract strategy. The reason three blocks were used instead of four was still to ease the participant into the prototype and prevent them from feeling overwhelmed. Room 2 also contained instructions for participants to use different parts of their hand to interact with all the blocks in each room.

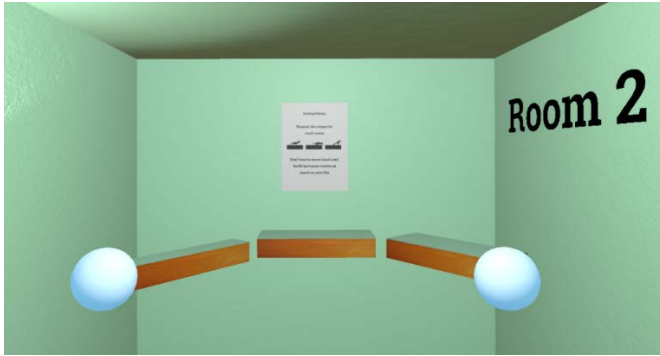


Figure 45: A screenshot of room 2 with the instructions shown in front the participant

Room 3

Block 1	Tonal abstract: squarewave
Block 2	Tonal abstract: triangle
Block 3	Tonal abstract: sawtooth

The purpose of room 3 was to introduce participants to the tonal abstract strategy. Again, the reason three blocks were used was to prevent the participant from feeling overwhelmed.

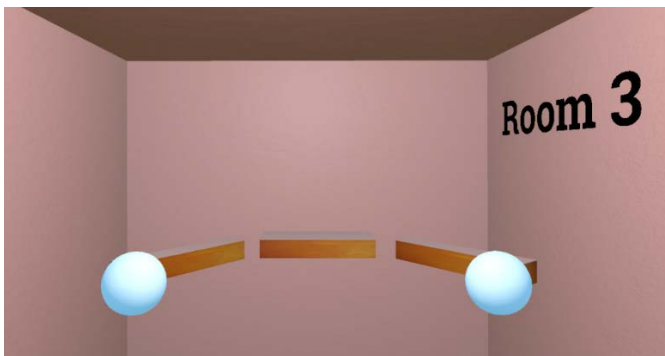


Figure 46: A screenshot of room 3

Room 4

Block 1	Pure texture: wool	Atonal abstract: sawtooth
Block 2	Pure texture: wool	Tonal abstract: triangle
Block 3	Pure texture: wool	Atonal abstract: sinewave
Block 4	Pure texture: wool	Tonal abstract: triangle

Room 4 was the first room to introduce combinations of implementation strategies and aimed to create different perceived textures in conjunction with the wool texture. In order to present a contrast in perceived textures, the (smooth) wool texture was combined with one smooth and rough tonal and atonal strategy each.

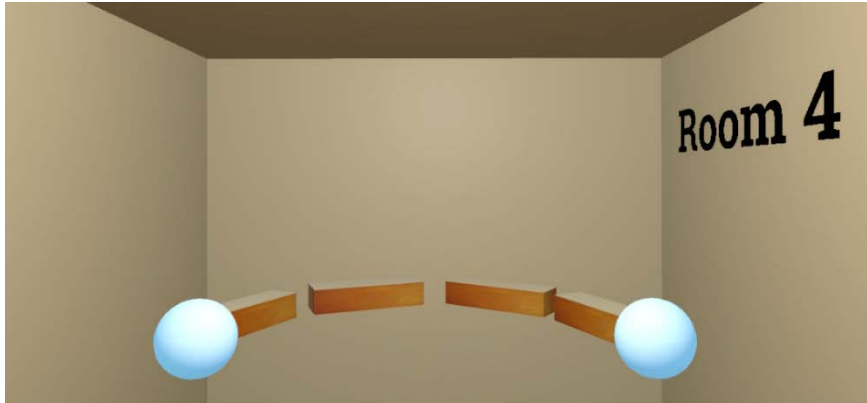


Figure 47: Room 4 was the first room to contain four blocks

Room 5

Block 1	Pure texture: sandpaper	Atonal abstract: triangle
Block 2	Pure texture: sandpaper	Tonal abstract: sawtooth
Block 3	Pure texture: sandpaper	Atonal abstract: squarewave
Block 4	Pure texture: sandpaper	Tonal abstract: sinewave

Room 5 can be thought of as an inverse of room 4 insofar as that it used the sandpaper texture but used a similar approach to combine a rough pure texture with both smooth and rough tonal and atonal strategies.

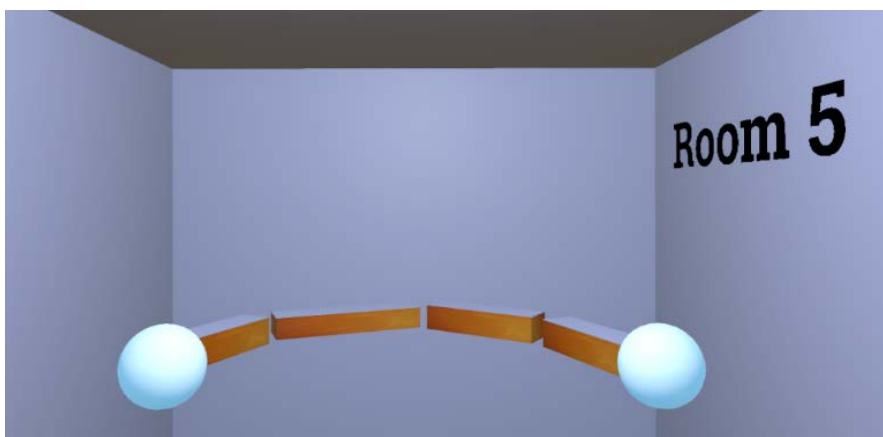


Figure 48: A screenshot of room 5

Room 6

Block 1	Tonal abstract: sawtooth	Atonal abstract: sinewave
Block 2	Tonal abstract: squarewave	Atonal abstract: sawtooth
Block 3	Tonal abstract: triangle	Atonal abstract: squarewave
Block 4	Tonal abstract: sinewave	Atonal abstract: triangle

The intent of room 6 was to combine the two abstract strategies in various configurations to explore consonance and dissonance between textures. The configurations explored possible combinations of using waveforms together that were both either smooth or rough, such as combining squarewave with sawtooth, as well as using these opposites together to create a contrast, such as combining sawtooth and sinewave. Both of these groupings were used with either texture as the waveform for the tonal and atonal strategy.

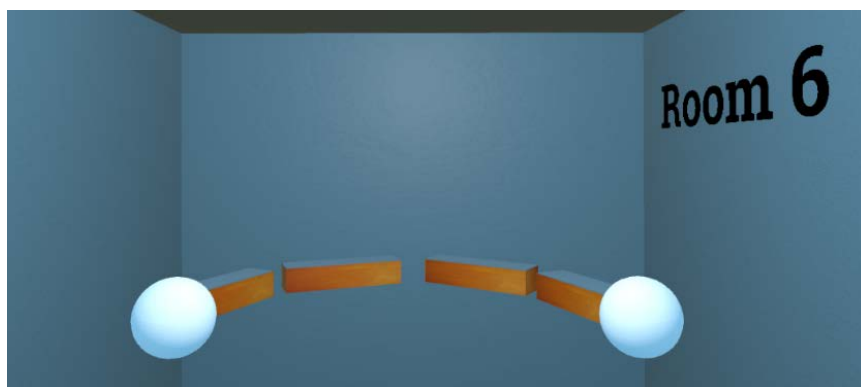


Figure 49: A screenshot of room 6

Room 7

Block 1	Pure texture: wool	Tonal abstract: sinewave	Atonal abstract: triangle
Block 2	Pure texture: wool	Tonal abstract: triangle	Atonal abstract: sawtooth
Block 3	Pure texture: wool	Tonal abstract: squarewave	Atonal abstract: sinewave
Block 4	Pure texture: wool	Tonal abstract: sawtooth	Atonal abstract: squarewave

This was the first of two rooms that simultaneously made use of three implementation strategies per block. The configurations of the abstract strategies used were similar to those of room 6 in order to create combinations of similar and contrasting textures with both textures being used for both the tonal and atonal strategies.

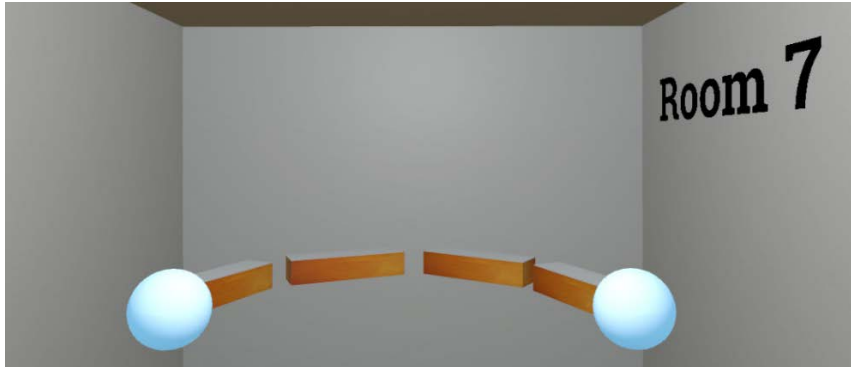


Figure 50: A screenshot of room 7

Room 8

Block 1	Pure texture: sandpaper	Tonal abstract: triangle	Atonal abstract: sinewave
Block 2	Pure texture: sandpaper	Tonal abstract: sinewave	Atonal abstract: squarewave
Block 3	Pure texture: sandpaper	Tonal abstract: sawtooth	Atonal abstract: triangle
Block 4	Pure texture: sandpaper	Tonal abstract: squarewave	Atonal abstract: sawtooth

The final room also made use of all three implementation strategies with a similar intent as room 7, but with different waveforms used in order to differentiate it from the previous room. The last room also provided the user with instructions encouraging them to return to previous rooms in order to thoroughly explore different tactile blocks and mentally make note of their experiences, as well as telling them to remove the headset when they feel they have explored enough. These instructions were purposefully left until the last room in order to prevent reminding participants about the end of the experience, and thus the researcher and the research environment, until necessary in order to maximise the amount of time they could spend disconnected from the real world, with the intent of increasing immersion (Slater & Wilbur 1997; Slater 2003).



Figure 51: A screenshot of room 8. The final instructions were shown in front of the participant and there was only one teleportation mechanism, since there were no additional rooms to traverse

When the user has removed the headset, they were given some time to readjust after the experience, at which point the interview took place.

4.3 Summary

This chapter has included a discussion of all the relevant details regarding the prototype which participants interacted with during the usability test. First, the hardware used was discussed, including the HMD and interaction mechanism, i.e. the Leap Motion. Broad details regarding the development of the prototype, specifically the development environment and SDKs used, were then discussed, followed by the broad goals and constraints of the system and how these were met, including design heuristics to guide development. The structure of the prototype was then laid out, including the design of the different rooms, the implementation strategies that were used to attempt to create illusory touch sensations, and the use of the various strategies across the prototype. The next chapter discusses all the results gathered from usability testing, including the pilot usability test and the main usability test.

5. Chapter 5 - Results

This chapter discusses the results obtained from the main research method: the usability test. This includes the results from the pilot usability test and how they informed changes in the final usability tests, as well as the results from analysing the data from the usability tests, which constituted the main research data for this study.

Quotations from participants are noted with inverted commas and are kept as close as possible to the original with spelling/grammar mistakes as well as colloquialisms indicated with [sic]. However, for the sake of brevity, connecting words or phrases such as “*uhm*”, “*like*”, etc. are included only where removing them would negatively affect readability or alter the meaning of the sentence. Some of the quotes were translated from Afrikaans by the researcher. For discussions that included more than one participant, each participant was referred to by a unique number, starting at one. However, for the sake of anonymity, participants are not consistently numbered across discussions, in other words, for every new discussion, the numbering used to refer to participants in that context is restarted from one. Where appropriate, referring to specific participants is shortened to “*P*” instead of “*Participant*”, for example “*P1*” to refer to “*Participant 1*”. For statistical measures, \bar{x} is used to indicate mean and σ indicates standard deviation.

5.1 Pilot usability tests

This section discusses the results of the pilot tests and how these results informed changes in the final tests.

5.1.1 Changes to interviews

Pilot usability tests were done with three users, all in the previous VR- and/or gaming-experience category. The testing procedures and data collection methods were identical to those to be used for the final test and users were treated in the same manner as well. The first pilot test revealed a significant flaw in the interview structure, which was that the participant had difficulty remembering their individual experiences from each virtual room, despite the use of colours and numbering to aid this recall. This was problematic since, in order to gain as much information from participants as possible regarding their experiences and the specific implementation strategies and their interplays, participants were asked to discuss their sensory experience of each room in turn. A possible strategy to counter this problem was to reduce the number of rooms in order to make it easier for participants to remember each room separately. However, this would have reduced the variety of combinations of implementation strategies that could be tested and would thus have introduced the possibility

of omitting what could potentially be the most effective combinations of strategies. Thus, the prototype was not altered for the main usability test.

Instead, this shortcoming was addressed with two changes in the test, the first being to encourage participants to pay attention to individual rooms and try to remember as much detail as possible before removing the headset. The interview structure was also altered so as to allow participants to return to the prototype if they could not recall the details of a specific room. However, this change came with two caveats:

- Participants' recollection of the specific room might be different to what they experienced the first time.
- Participants' second encounter might influence their first, for example, it might cause them to forget or falsely remember details from their first encounter based on their second.

For this reason, notice was taken during the interview when participants re-entered the prototype to recall details of a room, as opposed to recalling details of a room without re-entering. This was done in order to distinguish between "first-order" and "second-order" recollections, i.e. between recollections and recollections of recollections. Participants were also asked whether their experiences after re-entering the prototype were recollections of their first encounter with the prototype or whether they were newly-formed experiences from their second encounter.

The other two pilot usability tests confirmed the difficulty participants had in remembering all the rooms of the prototype, but the second and third pilot tests made use of the modified interview method, allowing participants to revisit the prototype if they were unable to remember the details of a particular room. This change was found to be an effective way to gather detailed feedback about each room and was found to lead to both recollected data as well as data from newly formed experiences, as anticipated. When participants seemed to have difficulty remembering a room, they were told that they can revisit the prototype. This strategy, however, was found to rely on the researcher's ability to discern when a participant was having difficulty remembering. For this reason, the interview structure was slightly modified again to inform participants that they could re-enter the prototype before asking questions regarding specific rooms, instead of during.

The wording of some of the interview questions were also changed based on answers and feedback from the pilot interviews. One question related to what participants experienced in terms of each sense in each room, which was found to cause participants to spend a significant amount of time discussing unrelated issues in different sensory modalities, such as

the colours of the walls. This was found to be potentially problematic, as participants might not discuss the focal topics enough to give valuable data/insights. Thus, to keep the interview data focused, this question was changed to focus on “notable sensory experiences” instead of asking about all sensory experiences. Another question required participants to discuss their experience while interacting with the blocks, which was found to be confusing, as participants were not sure whether this referred to the blocks in the introductory room or the tactile blocks. This question was thus changed to specifically refer to the tactile blocks.

One participant also had initial difficulty verbally expressing their experiences, because they were unsure that they were using the “correct” terminology. For this reason, the pre-interview primer was updated to, along with informing participants that there are no correct or incorrect answers, also encourage them to use their own wording or terminology to express their experiences and that there is no correct or incorrect terminology to use for this purpose. Finally, as per the recommendation of one participant, the pre-test procedure of helping the participant get started with the test was modified to inform them that the researcher would not be watching them perform the test but would instead wait outside the testing room until they are done. This was due to a concern that participants would feel self-conscious about their actions and behaviour during the test, as confirmed by one participant, which could have a negative effect on their immersion during the test. Furthermore, the modified procedure would not present a problem for data collection, as the test would still be recorded in the form of video-recording and screen-capturing. While corroborating interview and observation data, it was also found that allowing participants to revisit the prototype presented a problem with regards to observation data, which was that, due to ethics concerns, the interviews were not being video-recorded and thus there were no observation data for rooms that were revisited. The solution to this problem for the final testing was to let only the screen-capture software keep recording during the interview, as this allowed some observation data to be recorded without capturing video data which could be used to identify a participant, thus avoiding ethics concerns.



Figure 52: The researcher interacting with the prototype

The interviews, in turn, also revealed changes to be made regarding the details of the focus group, which are discussed next.

5.1.2 Changes to focus groups

The combined use of the ITC-Sense of Presence Inventory (ITC-SOPI) and an interview question to divide participants into groups based on previous VR- and/or gaming-experience revealed the importance of triangulation between different data collection methods, as participants rated their own experience levels significantly differently. For example, one participant who had an introductory theoretical knowledge and no VR development experience rated themselves as having “intermediate” knowledge of how VR works on the ITC-SOPI, whereas another participant with more substantial theoretical knowledge and previous development experience rated their VR knowledge as “basic”. For this reason, the grouping of participants was made at the discretion of the researcher based on their answer on ITC-SOPI as well as their motivation of this answer.

Another change informed by both the pilot studies and the interviews, and confirmed by the focus groups, related, again, to the recollection of details of individual rooms. Interviews confirmed the difficulty participants had in remembering individual rooms and thus it was necessary to allow nearly all participants to return to the prototype if they could not recall a specific room. Because of this, questions were removed from the focus group which asked participants to recall each room in turn, as it was expected that participants would have even more difficulty remembering individual rooms a couple of days after the experiment than they had directly after the experiment. This expectation was confirmed, as participants had difficulty relating specific experiences to specific rooms, which one participant described as follows: *"I didn't really focus on the room, I just focused on the blocks. So, when you asked me later on 'in which room?' I couldn't relate to in which room what happened. I just remembered working with the blocks"*.

Instead, preliminary analysis was done on the interview and observation data prior to the focus groups in order to identify preliminary topics that were frequently mentioned or behaviour that frequently appeared during observations. Questions were then created in order to further explore these topics, confirm suspicions, and resolve unresolved issues, which replaced the questions which would have focused on individual rooms.

The next section discusses the results obtained from all data collection methods regarding the main research method: the usability tests.

5.2 Usability tests

Usability tests were done with 23 participants in total, 11 of whom fell into the previous gaming- and/or VR-experience group, which is referred to from this point onwards as the expert group, and the remaining 12 into what is referred to from this point onwards as the non-expert group, based on their answers on the questionnaire and their explanation of these answers. Of the 23 participants, 14 had never used a virtual reality device before (this included all participants from the non-expert group) and of the nine that had, five had never used the Leap Motion device before, as illustrated in Figure 53 below.

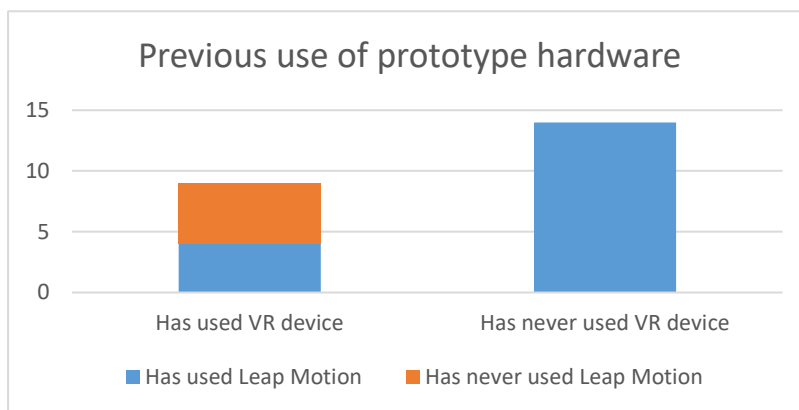


Figure 53: Participants' distribution according to established groups and previous use of hardware used in the prototype

For the ITC-SOPI item “Rate how often you play computer games”, participants who indicated that they play computer games “50% or more of days” were regarded as having significant gaming-experience, whereas gauging participants’ VR-experience relied on their explanation of their knowledge rating on the questionnaire. The distribution of participants according to these categories is illustrated in Figure 54 below.

Participants with previous development experience were automatically included in the expert group and participants who had used a VR-system before were included at the discretion of the researcher based on their description of the extensiveness of their experience. Two focus groups were held, the first one with six members of the non-expert group and the second with four members of the expert group, based on the availability of the participants as discussed in section 3.3.2.4. Before discussing the results that relate directly to the goals of the study, the prototype’s effectiveness in terms of comfort and usability is discussed in the next section.

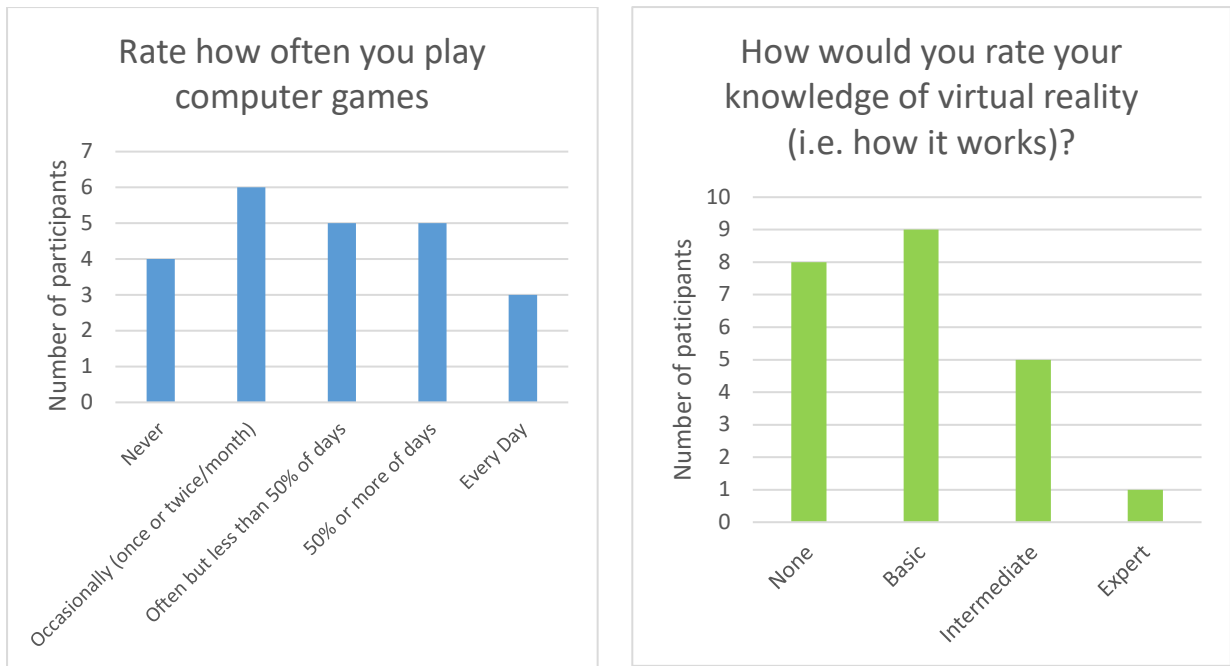


Figure 54: Participants' responses to questions regarding their gaming-habits and VR-knowledge

5.2.1 Comfort and usability

The first topic of the current section is that of motion sickness. As discussed in section 4.2.2.1, the prototype aimed to reduce visually-induced motion sickness by keeping users in a seated position and only allowing for movement between virtual rooms by means of a virtual teleportation mechanism. This strategy proved to be effective, as participants noted very low levels of nausea on the ITC-SOPI: $\bar{x} = 1.56$, $\sigma = 0.84$ (it should be noted that all ITC-SOPI scores range from 1 to 5 with 5 indicating "Strongly Agree"); the overall spread of ratings for this item is illustrated in Figure 55 below. The overall "negative effects" score given on the ITC-SOPI, which combines the scores for disorientation, fatigue, dizziness, eyestrain, nausea, and headaches, was also low ($\bar{x} = 1.93$, $\sigma = 0.76$), with the highest-rated factor being disorientation ($\bar{x} = 2.48$, $\sigma = 1.12$).

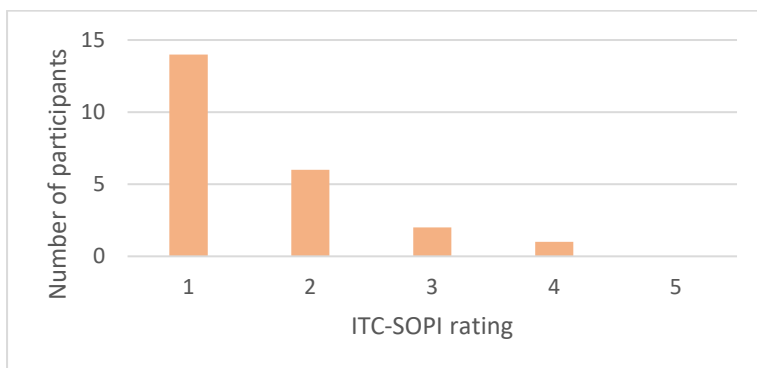


Figure 55: ITC-SOPI Ratings for "I felt nauseous"

Only two participants mentioned nausea during any of the data collection methods, the first noting the following: “*The soft colours that you used in the room, I like it, because it isn’t too visually straining. I didn’t feel nauseous or anything during the whole experience and it’s a calming feeling*”. The second participant who mentioned nausea noted, in their interview and open-ended questionnaire question, that some of the sounds produced by some of the blocks made them nauseous, because “*...if I rubbed [the block] too long it felt like it vibrated and then I get sick*”. Thus, having the option of preventing participants from moving around in the space and having to move them in virtual space, the teleportation option is considered successful for the current study in preventing motion sickness during the usability test. With regards to fatigue, two participants, one of whom is the participant mentioned above who felt sick due to some of the sounds, noted that interacting with the prototype made their arms tired. However, the low number of participants who noted fatigue and the low fatigue score on the ITC-SOPI ($\bar{x} = 2.09$, $\sigma = 1.16$) suggest that fatigue, generally speaking, was not prevalent during the usability test.

With regards to usability as well as overall presence levels, the current section refers to the heuristics put forth by Sutcliffe and Gault (2004) as discussed in section 4.2.2.2. The effectiveness of each heuristic property in the prototype is discussed in turn by referring to collected data.

5.2.1.1 Natural engagement

In order to assess the effectiveness of this property of the prototype, the following five items of the ITC-SOPI were examined, with the last item being the closest to the goal of the heuristic:

- B5 - *The displayed environment seemed natural*: $\bar{x} = 3.43$, $\sigma = 1$
- B19 - *I felt that I could move objects (in the displayed environment)*: $\bar{x} = 4.6$, $\sigma = 0.66$
- B33 - *I felt able to change the course of events in the displayed environment*: $\bar{x} = 4.17$, $\sigma = 1.03$
- B35 - *I had the sensation that parts of the displayed environment (e.g. characters or objects) were responding to me*: $\bar{x} = 4.83$, $\sigma = 0.39$
- B36 - *It felt realistic to move things in the displayed environment*: $\bar{x} = 4.39$, $\sigma = 0.89$.

As these results show, participants felt a strong sense of being able to enact changes on the environment and experienced that the manner of enacting these changes “felt realistic”. This was supported by interview data, such as the following: “*It felt like a real room, it felt like I was sitting there doing things. The objects looked realistic, it looks like I can touch them*”. Whereas interaction in the main rooms came across as natural, a number of participants expressed

difficulty in interacting with the blocks in the introductory room, as participants expected these blocks to be able to be picked up, which they were not. However, since the purpose of the introductory room was not to gather any data, this was not regarded as a problem with regards to the purpose of the study. Another instance where interaction was perceived as unnatural occurred when the Leap Motion device temporarily lost tracking of a participant's hand, which would cause momentary erratic behaviour, such as jittery movement or an inversion of the virtual hand on the vertical axis. One participant described their experience as follows: *"It felt a bit strange sometimes. Not the interaction itself, sometimes if the hand went through [the blocks] or something like that. Sometimes it got stuck and then it was a bit strange"*. However, for the main rooms, comments that indicated the naturalness of the interaction were far more frequent than comments that indicated otherwise.

5.2.1.2 Compatibility with the user's task and domain

As this heuristic's notion of expectation regarding objects and interactions in the VE overlaps with the previous heuristic, one item from the ITC-SOPI was repeated in the investigation of this heuristic:

- *B11 - The content seemed believable to me: $\bar{x} = 3.83, \sigma = 0.94$*
- *B15 - I felt that the displayed environment was part of the real world: $\bar{x} = 3.17, \sigma = 1.27$*
- *B20 - The scenes depicted could really occur in the real world: $\bar{x} = 3.43, \sigma = 0.90$*
- *B28 - I felt I could have reached out and touched things (in the displayed environment): $\bar{x} = 4.65, \sigma = 0.57$*
- *B36 - It felt realistic to move things in the displayed environment: $\bar{x} = 4.39, \sigma = 0.89$.*

Some participants noted that some of the objects in the VE did not behave as they would expect objects to behave. As already mentioned, a number of participants found the behaviour of the blocks in the introductory room unnatural. Other participants also noted a mismatch between their expectations and the behaviour of the blocks that produced abstract sounds, as expressed by one participant: *"This one's sounds sounded unnatural. It made more sci-fi type sounds"*. However, as the abstract sounds formed part of the experimental setup, they were considered a necessary component of the experiment. With regards to affordances for task action, the high score given for item B28 indicated that the main task action, rubbing blocks, was given adequate affordance by the prototype. With regards to the VE in general, many participants noted that the environment looked realistic, as illustrated by the following remark: *"I was looking at details and that made it more realistic, so I didn't have one instance where it felt... it took me out of the presence of the virtual reality world"*. With regards to environmental audio, none of the participants noticed the room tone which was constantly playing in every room, as discussed in section 4.2.2.3.1, which was considered a desirable

outcome, since the purpose of the room tone was to make the rooms seem more natural without necessarily drawing attention to itself, since the environment which the VE aimed to model is relatively quiet. Participants also did not note anything regarding the teleport sounds, which was also considered desirable, since these sounds only served to indicate a successful action: teleportation between rooms. Since, as is discussed below, participants generally found it easy to navigate between rooms and could learn this mechanism easily, the absence of attention on these audio cues suggests that they successfully served their purpose.

5.2.1.3 Natural expression of action

The ability of the prototype to make use of the Leap Motion to allow users to use their hands in a natural way was received positively, as expressed by one participant: “*The hands were a good touch, it made me feel like those were my real hands that can touch things*”. The naturalness of interaction via the virtual hands was also expressed in the way participants referred to the use of their hands, for example: “*Felt as if I was connecting better [sic] with the blocks when I was using the fingertips and top of my hands to touch the blocks*”. It should be noted that this use of language makes no distinction between their physical hands being tracked in the real world and the virtual representation controlled by their actions. This tight coupling between the user’s hand and the virtual hand-representations also indicated a high level of the matching/interactivity aspect of immersion and a moderate level of the egocentric virtual body representation aspect (Biocca 1999), as participants experienced little separation between their motor actions and the system response and also felt that they “inhabited” their virtual hands. Three participants, however, noted that absence of a virtual body made them feel like a “ghost” in VR, which is discussed further in section 5.2.4.2.2.

5.2.1.4 Close coordination of action and representation

As mentioned in section 5.2.1.1, the Leap Motion device occasionally lost tracking of a participant’s hand, which resulted in a temporary mismatch between their motor actions and the visual representation of the virtual hand. No participants noted a mismatch between head movement and virtual head movement and the low rating for motion sickness suggests that the latency between participants’ head movement and virtual head movement was sufficiently low at all times.

5.2.1.5 Realistic feedback

As the topic of realism and believability lies at the core of participants’ experience of touch and thus at the core results of the current study, these factors are not discussed here in full, but are discussed in section 5.2.4.3. However, data from the questionnaire can be used to assess participants’ experience of realism and reliability. The ITC-SOPI divides results into three separate factors, one of which is ecological validity which refers to “*a tendency to*

perceive the mediated environment as lifelike and real” (Lessiter et al. 2001) and had a mean and standard deviation of 3.57 and 0.74 respectively. Furthermore, the moderately high scores for items B11 and B20 and high score for item B36, as listed above, specifically indicate that participants tended to experience the prototype’s response to their actions as realistic and meeting their expectations. Only one participant commented on an unnatural aspect of the behaviour of the tactile blocks, noting that they “...found it weird that [the block] levitates, but there isn’t really anything that is holding the block”. When this topic was brought up during the non-expert focus group, one participant noted that: “You almost go into the VR, the system, with an open mind and I didn’t mind if I saw blocks hovering because I was like ‘cool, I’m going into this kind of space where things like this are possible’ [sic]. So, it didn’t seem unrealistic, even though it is unrealistic”. Another participant in the expert focus group justified this discrepancy by stating: “I’d say also willing suspension of disbelief, like, you’re in it, the first thing you see is the environment and it doesn’t change, it’s consistent the whole way through, so you accept that as what it is and so it’s still real, it doesn’t matter if it’s not real, like real-life real [sic]”. Participants also agreed that their sense of realism during the experiment was malleable.

5.2.1.6 Faithful viewpoints

The implementation of the prototype with a first-person camera view using the SteamVR API ensured that the VE was always represented from the participant’s normal perception and, as discussed in section 5.2.1.4, the delay between physical and virtual head movement was sufficiently low.

5.2.1.7 Navigation and orientation support

Each room was given a unique colour and the room number was indicated on the wall, as shown in section 4.2.2.6, Figure 44. Navigation was done with the use of a teleportation mechanism which transported participants between rooms, which video-recording and screen-capture data indicated participants found easy to use, with the exception of two participants who could not find the teleportation mechanism in the introductory room and had to be told where it is, which was expected to have had an adverse effect on their overall immersion and presence. Since participants remained seated during the experiment, there were no problems regarding locomotion and orientation.

5.2.1.8 Clear entry and exit points

Participants were told that the experiment would start as soon as they saw the introductory room (and that communication with the researcher would cease at that point). As discussed in section 4.2.2.2, there was no exit “point” by which participants closed the application, but

rather an instruction telling them to take off the headset and inform the researcher when they had explored enough.

5.2.1.9 Consistent departures

The teleportation mechanism was explained in the introductory room and was consistent throughout the experiment which, as explained above, was generally regarded as simple and easy to use. Regarding cross-modal substitution, as it is closely related to the main research goal of the current study, this topic is not discussed at this point and is discussed further in section 5.2.3.1.

5.2.1.10 Support for learning

Interaction methods were either explained in the prototype via text- and graphics-based instructions or were perceived as affording certain actions; specifically, the blocks were perceived as affording rubbing and pushing. Screen-capture data show that most participants could use the prototype without difficulty, with the exception of the two aforementioned participants who had difficulty finding the teleportation mechanism in the introductory room and one participant who initially only pushed down blocks and did not rub them, and thus had to repeat the experiment. Thus, the action of appearing in a different space along with the audio feedback which accompanied teleportation appeared to sufficiently teach participants the workings of the teleportation mechanic. With regards to general interaction however, since the Leap Motion was used as the main interaction mechanism, it is not expected that the core skills that participants learned in order to traverse and interact with the prototype would be transferable to most VR systems, as these systems do not come standard with a Leap Motion, but instead tend to use hand-held controllers (HTC Corporation 2018; Oculus 2018).

5.2.1.11 Clear turn-taking

As discussed in section in section 4.2.2.2, this heuristic was not applicable to the current study.

5.2.1.12 Sense of presence

As discussed in section 5.2.1.5, the ITC-SOPI divides overall sense of presence into three separate factors (Lessiter et al. 2001), one of which (ecological validity) has already been discussed. The other two factors are listed here with their mean scores and standard deviations:

- *spatial presence – a sense of being there:* $\bar{x} = 4.11, \sigma = 0.4$
- *engagement – psychological involvement and enjoyment:* $\bar{x} = 4.05, \sigma = 0.47$.

The overall high score for presence was in line with participants' comments, for example: *"It was strange, at one point I was looking at my hands and then looked down and there were no arms, and I was somewhat surprised, and then looked down and there weren't any legs or a chair or anything and I found it surprising that these things weren't there, because it felt as if I was in a different place"*. All participants expressed enjoyment after using the prototype, except two participants, one of whom expressed neither enjoyment nor displeasure, and the other expressing frustration due to tracking problems related to their hands. As discussed above, participants tended to perceive interactions as natural based on their expectations, except for when there were tracking issues and with regards to some of the digital sounds.

This section started with a discussion on the comfort levels provided by the prototype as discussed by participants in quantitative and qualitative results. The well-known issue of motion sickness was addressed and found to be below a satisfactory threshold. Broad goals of usability and presence levels were then discussed by individually discussing heuristics put forth by Sutcliffe and Gault (2004), again using a combination of quantitative and qualitative results (Sutcliffe & Gault 2004). These results also indicated satisfactory levels of usability as participants could easily use the prototype and found it to align with natural hand-actions such as rubbing and pushing. Presence levels were also found to be high, with many participants describing an experience of being physically transported to the virtual space while using the prototype.

Having discussed all matters regarding comfort and usability, the next section discusses illusory sensations experienced by participants that were not the goal of the current study.

5.2.2 Unintended illusory effects

Some unintended illusory perceptions were experienced by some participants while interacting with the prototype: kinaesthetic feedback while interacting with the blocks, a differing sense of temperature and room size between the rooms, and a difference in sound depending on how the blocks were rubbed. These are discussed in turn.

5.2.2.1 Illusory kinaesthetic feedback

Although none of the interview questions were directed at illusory kinaesthetic feedback, five participants noted that they felt a sense of force feedback while interacting with the block, as illustrated in the following remarks and exchanges:

- *"I think all of them felt, I felt a little bit of resistance pushing down, because I think as I touched it I think the sound was made, so all over that little bit of like... I can't just go [gesture of pushing down]."*

- *“Apart from touch, when you actually take the blocks higher, you can actually feel the weight of the blocks, I don't know if that makes sense? When you just take your hand a bit higher, it's as if you can actually feel the block on the top of your hand, apart from you rubbing on the surface of the block, when you take it higher you can actually feel the weight of the block.”*
- **Participant:** *“The one [block] that makes a very, very low noise is, I don't know, heavier, harder to...”*
Researcher: *“To push down?”*
Participant: *“Yes, it's almost as if when you rub over these [room 6, first two blocks], just rub them, you rub them down, but here [rubs other blocks]... I don't know, it feels as if these ones [first two blocks] can easily be pushed and these [block 3 and 4]... well not now, because I don't have the headphones on.”*
Researcher: *“So it doesn't work if you don't have headphones on?”*
Participant: *“No.”*
Researcher: *“So the sound makes it feel heavier for you?”*
Participant: *“Yes, it's just more difficult [sic].”*
Researcher: *“What about the sound makes it different?”*
Participant: *“From these [block 1, 2, and 3]? I don't know, the only difference that I can hear is that the sound is lower, but for some reason it makes me feel that it is... heavier. (Laughs) I don't know.”*

It should be noted that the last participant above is one of the participants who noted some fatigue in their arms during the experiment. It is also worth reiterating at this point that participants were not in contact with any physical objects or devices and that the Leap Motion, responsible for tracking their hands, is unable to create any kinaesthetic feedback. The vertical movement of the virtual blocks was always in proportion to the vertical displacement of their own hands (unless, as stated, there were tracking problems) and this vertical movement was not altered or distorted at any point. Therefore, each block behaved exactly the same way in reaction to being pushed down and no part of the prototype hardware could have exercised any physical force on participants' hands. There were also no differing visual cues to suggest a mismatch between hand movement and block displacement, so each block simply moved in relation to participants' downwards hand movements. The association between weight and low pitch is in line with findings by Walker, Scallon and Francis (2016) who found that participants tend to expect heavier objects to make lower-pitched sounds (Walker, Scallon & Francis 2016).

The topic of a “sense of pressure when pushing the blocks” was followed-up on during both focus groups, which led to the following exchanges:

Non-expert focus group

- **Researcher:** “Another topic that came up during the interviews was a sense of pressure when pushing the blocks. Did anyone experience something like this?”
- **P1:** “Yes, especially when pushing it down you sort of feel like it wants to go back up, and that is laid bare when you move your hand. It automatically goes back to its normal position.”
- **Researcher:** “So, the feeling of your hand being pushed up goes away when you remove your hand from the block?”
- **P1:** “Yes.”
- (General agreement from other participants)
- **P2:** “So it’s like resistance.”
- **P1:** “Yeah.”
- **Researcher:** “Can anyone tell me why they think this happens?”
- **P2:** “Maybe it’s because you’re imagining that ‘ok, there’s a block and I want to push it down’ and by doing that it feels like ‘ok, obviously if you push something down it wants to come up naturally’. I don’t know, maybe.”
- **Researcher:** “So, sort of to do with how you would expect it to do it in the real world?”
- **General agreement:** “Yes.”

Later in the same focus group, during a summary question (Morgan, Krueger & King 1998:3):

- **Researcher:** “Who did not experience any sense of pressure?”
- (No response)
- **Researcher:** “So, there was a sense of pressure when pushing down on the blocks. Was it more on the ‘down’ or more on the ‘up’ that you experienced the sense of pressure? Or was it about the same?”
- **Some participants:** “Down.”
- **Researcher:** “Did anyone experience more of a pressure pushing it up?”
- **P1:** “There would be a sense of pressure, I mean you get a sense of gravity when you push it up; as soon as you let it go it comes down. I think ‘ok, it has to come back to where it initially was’. But then when you push it down, even the sound effects, and as soon as you let it go it comes back to where it was.”

Although the presence of an illusory kinaesthetic force was not a goal in the design of the prototype, it is not entirely unexpected, as it bears some resemblance to a similar phenomenon observed by Biocca, Kim and Choi (2001) and Biocca et al. (2002) which involved participants also observing a sense of physical force where none was present (Biocca, Kim & Choi 2001; Biocca et al. 2002). However, whereas the two aforementioned studies visually represented an analog of a haptic force by using a visual representation of a spring which “connected” a moveable object to its source location (Biocca, Kim & Choi 2001; Biocca et al. 2002), the current study did not make use of such a representation to connect blocks to their default position. The data shown above suggest that the behaviour of the block, in terms of its movement and the sound that resulted from touching it, was enough for some participants to experience it as having physical properties, specifically weight and resistance, and that these physical properties caused these participants to experience illusory kinaesthetic feedback. Furthermore, as discussed above, the association between low pitch and increased object weight was also in line with existing findings (Walker, Scallon & Francis 2016). Similar findings were also obtained from the expert focus group.

Expert focus group

As one of a series of transition questions (Morgan, Krueger & King 1998:3), participants were asked about their experience of the blocks exerting force on their hands.

- **Researcher:** *“Another thing that came up during the interviews was a sense of the block pushing back. Did anyone experience that?”*
- **P1:** *“Yes, I experienced that.”*
- **P2:** *“Like, you physically feel like the block is pushing back?”*
- **P1:** *“When you press on one of the boxes, you actually feel it, it's as if it's trying to get up.”*
- **P3:** *“Really?”*
- **P2:** *“I didn't feel anything literally pushing back...”*
- **P3:** *“Me neither.”*
- **P2:** *“...but you get the... you know what's going to happen when you lift your hand away, it's going to bounce back to where it was.”*
- **Researcher:** *“Ok, so you [Participant 2] didn't feel any sort of force feedback, but you [Participant 1] did?”*
- **P1:** *“I actually felt... it's as if the blocks... the only motion they're able to move is upwards, not downwards, because when you press them downwards you actually feel a force... just, opposing force, but when you just put them up [sic] they go up.”*

- **P3:** *"I guess I felt something little bit like that, but I didn't actually think about it before."*
- **P1:** *"It's actually difficult to take them down, but it's easy to just take them up [sic]."*
- **P3:** *"Yeah, that makes sense."*
- **P4:** *"I didn't feel anything that... it's interesting, but..."*
- **Researcher:** *"Why do you think you experienced this?"*
- **P3:** *"I think it's because of the sound, I don't know why, maybe the sound made it feel more like a block."*
- **P1:** *"Yes. And maybe the blocks were just programmed to go a bit slower down? [laughing] I don't know, I don't do programming."*
- **P4:** *"I just want to add that I would say, hypothetically speaking, that if you made it that the harder you push down, the harder the board comes back up, I would be more inclined to feel what you were saying."*
- **Researcher:** *"Can you elaborate on that?"*
- **P2:** *"So, the further you push it, the more resistance you get."*
- **P4:** *"Yeah, so the further you push it down, and also the speed at which you push it down, and then when you release it..."*
- **P1:** *"Springs back up."*
- **P4:** *"Yeah, springs back up in proportion to the force that you pushed it down with."*
- **Researcher:** *"So if you pushed it further down it goes back up faster?"*
- **P1 & 4:** *"Yes."*
- **Researcher:** *"And this would hypothetically have a better effect on your sense of force?"*
- **P1 & 4:** *"Yes."*

It should be noted that participant 3 was not one of the participants who noted a sense of kinaesthetic feedback during their interview. The fact that, although this participant was initially surprised at participant 1's experience of physical force, but later came to recognise it in their own experience, suggests that other participants who did not take part in the focus groups may have also experienced a sense of physical force, but did not recognise it as such, since data with regards to this topic were not collected as part of the usability test, because it was not part of the initial goal of the study. However, it is also possible that participant 3 was adjusting their opinions and experiences to match those of other group members, which is known to occur during focus groups (Morgan, Krueger & King 1998:1; Taylor, Bogdan & DeVault 2015:4).

The perception of weight when lifting a block can be partially explained as a side effect of performing motor actions in the real world (Lecuyer, Cuquillart & Coiffet 2001), since participants had to lift their hands in the air to lift the blocks, during which the effects of gravity would naturally pull their hand back down. However, this explanation was never raised during the interviews or focus groups. Furthermore, the same reasoning cannot be applied to explain the illusory resistance when pushing blocks down, since gravity would naturally pull participants' hands down, making it "easier" for them to push blocks down. The above data suggest that an important factor in inducing an illusory sense of force was the perception of the block as a believable physical object with physical properties that correspond with participants' expectations from the real world, as illustrated in the remark that the block "*wants to come up naturally*" or that the sound "*made it feel more like a block*". This is supported by participant 4's comments during the expert focus group, during which the participant suggests a change in the block's behaviour which would meet their expectations and have a better chance of inducing a sense of force. However, as the bulk of the data collection did not focus on this phenomenon, there are not sufficient data to support further claims and thus the phenomenon is not discussed further.

5.2.2.2 Room effects

A less-frequently observed phenomenon which, like the illusory kinaesthetic feedback, was not explicitly targeted during the interviews, was that of the different rooms causing different illusory sensations. The first of that which is discussed is the illusory perception of temperature, which was noted by two participants, as illustrated in the following remarks and exchanges from interviews:

- "*Well, now that I'm paying attention, this room feels a bit warmer than the previous one.*", "*Temperature also feels a bit lower.*", "*[this room] also feels a bit cooler and large.*"
- "*I think everything was the same, but the colours obviously make a difference for me, like, this room feels warmer.*", "*Also a warm feeling though, the colour was, not warm, cold, sorry. Cold feeling.*"

The second participant above also noted the following during the non-expert focus group:

- **Participant:** "*I also felt [a sense of temperature]. I don't know, almost automatically when I was in the blue room I felt a sense of... coldness. And when I was in the green room, that was peaceful, the temperature, you almost... your mind is really weird when no senses are actually working, but all your senses are actually working. That makes no sense, but in that kind of environment I think, because it's a virtual environment your*"

imagination kind of goes with it and that's what happened with me. So, the colours really made a difference to my perception of each room and the feelings that I felt in each room."

- **Researcher:** *"So all of your senses are working as if you're there?"*
- **Participant:** *"Yes, and not physically here."*

The fact that the first participant noticed the temperature sensation after "*paying attention*" suggests that their perception after returning to the prototype during the interview might have been influenced by the ITC-SOPI question regarding temperature differences: *"I sensed that the temperature changed to match the scenes in the displayed environment"*. However, the second participant's remarks regarding how *"no senses are actually working, but all senses are actually working"* is indicative of the illusion of having an unmediated experience, since this participant would need to feel that they are interacting with the environment directly in order to feel a sense of temperature without the necessary feedback devices (Lombard & Ditton 1997). The participant was thus enacting a degree of suspension of disbelief which allowed their internal systems, specifically those regarding the perception of temperature, to react as if they were physically present in the VE (Slater & Usoh 1993; Regenbrecht, Schubert & Friedmann 1998). This suspension of disbelief forms a core part of the main goal of the current research, as discussed further in section 5.2.4.3.4.

Another less-frequent unintended illusory phenomenon is the illusory change in room size as a result of room colours changing. It should be noted at this point that there were no differences in size between the different rooms. However, two participants noted perceived changes in room size:

- *"Room 2 felt smaller than room 1 to me. I think it was darker.", "[this room] also feels a bit cooler and large."*
- *"Ok, here are more blocks [in this room]. They are closer now, I feel. Maybe the room is just smaller, is that possible?"*

The second participant above also noted the following during the non-expert focus group:

- *"I think the one room I said it felt like the room was smaller, probably because of the use of colour, the background. In that room I also felt a bit anxious, like 'ok, it's small I need to get out.'"*

While this phenomenon was unintended, it is also not entirely unexpected, as room colour has been known to affect the perceived size of a room (Oberfeld, Hecht & Gamer 2010; Jaglarz 2011). However, the fact that this illusion held true for these participants in a virtual space points further to the illusion of an unmediated experience, which allowed participants

to experience the VE as if they were physically transported to the space (Lombard & Ditton 1997; Slater & Wilbur 1997), which also forms part of the core of the main research as discussed in section 5.2.4.2.2. However, since this phenomenon was not explored in-depth during the interviews, there are not sufficient data to support further claims and thus the phenomenon is not discussed further.

5.2.2.3 Change in sound depending on hand position

Five participants also experienced a difference in the audio being played back in response to rubbing the blocks depending on which parts of their hands they used while rubbing. It should be noted that this functionality was not included in the prototype: the audio being played per block was the same regardless of how the hand was positioned and the only parameters that controlled the sound were the velocity of the hand and the displacement of the block, as discussed in section 4.2.2.4. Thus, remarks such as the following indicate an illusory change in audio:

- *“I liked how if you used the palm of your hand it makes a sound and with the back of your hand it also makes a sound and I like that it makes another sound.”*
- *“I liked that it made different sounds depending on how I touched it.”*
- *“Some of [the blocks] didn’t react so well if you rub them with your fingertips, it’s more with the back of your hand.”*

Upon inspecting the video recordings of the participants, it was found that some participants would keep their hands still and move their fingers around to rub the blocks. This would then cause the playback volume of the sounds to be quite low, since their hand velocity would be very low, thus explaining remarks like the last one listed above. However, apart from sound differences when using their fingertips, four participants still noted that the sound changed depending on which parts of their hands they used to rub the blocks.

One of the four participants above also noted that the sounds were different if they rubbed underneath the blocks:

- *“When I started [on the block on the left], the base of the block was clearer, the sound that came through, a different sound.”, “And on the right as well, with the outside [blocks] the sounds were clearer if you touched underneath, if I can put it like that.”*

Again, it should be noted that the sounds did not change depending on where a participant rubbed the block. An up-displacement would have the same result on the volume and sound parameters as a down-displacement, since all that was used to calculate the displacement was an absolute value of the displacement from the starting position, as discussed in section

4.2.2.4. However, since this phenomenon was not explored in-depth during the interviews, there are not sufficient data to support further claims and thus the phenomenon is not discussed further.

Although these illusions were not part of the focus of the current study, and thus were not focused on during data collection, their causes as described by participants allude to some of the causes of illusory tactile sensations. These include the perceived physical properties of the blocks and the rooms being believable enough for participants to attribute additional physical properties to them, such as weight for the blocks and temperature for the rooms.

Furthermore, participants' illusions of an unmediated experience allowed them to experience the environment and objects as real enough to induce these illusory sensations and to parallel known real-world illusions, such as the perceived room size changing based on the colour of the walls. These causes are revisited when discussing the causes of illusory tactile feedback in section 5.2.4.

Having discussed all non-central topics related to the study, the next section discusses one of the main focuses of the study, the effectiveness of the prototype in inducing an illusory sense of tactile feedback.

5.2.3 Illusory tactile feedback

This section begins by referring to the observation, questionnaire, and interview data to evaluate the effectiveness of the prototype in achieving its goal. This is followed with the details of the experiences and sensations of participants and the main themes present in these discussions.

5.2.3.1 Effectiveness in creating illusory tactile feedback

In order to evaluate the effectiveness of the prototype in inducing a sense of illusory tactile feedback, the interview questions included three key questions (Morgan, Krueger & King 1998:3) specifically related to this topic. However, it was expected that asking these questions too early in the interview would prime participants to frame their experience in terms of their touch-experience, which could lead to false positives. Therefore, these three questions were asked near the end of the interview, which then ended with a summary question regarding their overall experience (Morgan, Krueger & King 1998:3). These three key questions were as follows:

1. *In which room would you say what you experienced came closest to actual touch?*
2. *Can you elaborate on why that room's touch experience felt more real than the others?*

3. *How would you summarise your overall experience in terms of your sense of touch during the experiment?*

Thus, this section of the interview required participants to examine their experience in terms of their touch-experience and put that experience into words. However, as discussed in section 3.4.3, interviews are susceptible to intended as well as unintended fabrications from participants, possibly based on what they think the researcher wants to hear (Preece, Sharp & Rogers 2015:7; Taylor, Bogdan & DeVault 2015:4). Thus, care was taken to avoid revealing the goal and nature of the study to participants and therefore they would not know what it is they “should” have experienced. Care was also taken to avoid leading terms during any form of communication by keeping the terminology used in earlier questions broad, such as “*How would you describe your experience inside the virtual environment during the experiment, especially while rubbing the blocks?*” and “*How would you describe your experience in terms of any notable sensory experiences in the first room?*”.

Thus, for the purposes of the current study it was assumed that touch-experiences that were brought up before these three key questions were more indicative of a genuine illusory tactile sensation than experiences that were brought up in response to any of the aforementioned key questions.

From the 23 participants who were interviewed, the responses in terms of when a participant described a form of a tactile experience were as follows:

- 16 participants noted a tactile experience during the interview before the key questions.
- 2 participants noted a tactile experience in response to the key questions.
- 3 participants noted experiences that were contradicting with what they had expressed earlier in the interview.
- 2 participants clearly noted not having any tactile sensations.

Of the 16 participants who noted a tactile sensation before the key questions, 14 noted this during their interview, one participant noted it in their open-ended questionnaire question (which, as discussed, took place before the interview), and one participant showed clear behaviour of reacting to a tactile sensation (which is discussed further below), which was confirmed by their interview data.

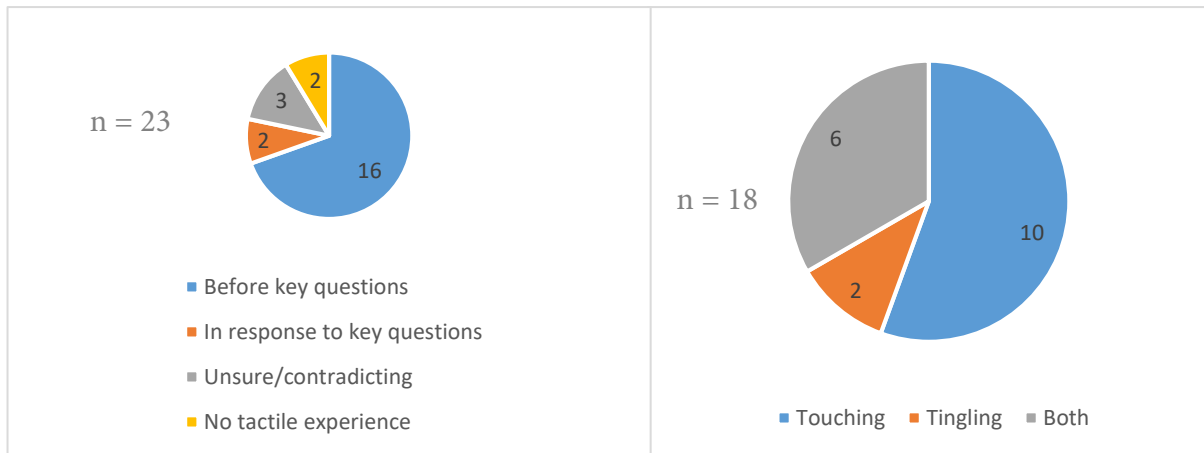


Figure 56: The left graph shows the point during data collection at which participants described having an illusory tactile experience, while the graph on the right shows what type of tactile experience participants described, divided into two types

Furthermore, three items from the ITC-SOPI were examined which were considered to be related to the illusory sense of touch in order to gauge the effectiveness of the prototype:

- B7 - I felt that the characters and/or objects could almost touch me: $\bar{x} = 4.09$, $\sigma = 0.95$
- B27 - I had a strong sense that the characters and objects were solid: $\bar{x} = 3.86$, $\sigma = 1.15$
- B28 - I felt I could have reached out and touched things (in the displayed environment): $\bar{x} = 4.65$, $\sigma = 0.57$.

The overall mean and standard deviation for the combination of these questions are as follows: $\bar{x} = 4.32$, $\sigma = 0.76$. One other question related to perception across multiple senses was excluded from this calculation: B31 - I felt that all my senses were stimulated at the same time ($\bar{x} = 3.22$, $\sigma = 1.04$). The reason for this is that it was expected that participants would interpret this to include their sense of smell, since an earlier question points to this perception: B22 - I could almost smell different features of the displayed environment. Multiple participants also pointed out during the interviews that they could not smell anything in response to the prototype, which further suggests that they would have included a sense of smell in their understanding of “all their senses”. Instances of low combined scores for these three items also corresponded with interview data indicating a low or non-existent sense of touch, for example, one participant with a low combined score ($\bar{x} = 2.67$, $\sigma = 1.15$) also stated the following: “I get a sense of the texture of what the thing should be, but obviously I don't feel anything”.

Descriptions of tactile experiences were regarded as unclear if participants noted contradicting experiences during the interview, for example, one participant noted early in their interview that they “obviously can't feel [the block]” but noted the following in response

to the second key question: *“It felt like I was touching it. I don’t know how to describe it”*. This sort of ambiguous response is in contrast with the type of responses that characterise the 18 participants (n = 23) who noted clear touch-sensations before or after the key questions, such as the following: *“I don’t know, to me it really felt as if I can feel [the block]”* and *“It’s so weird because I couldn’t feel anything, but it felt like I was feeling something”*. It should be noted that what is regarded as a touch-sensation for the current study is divided into two broad types based on descriptions by participants: a touch-sensation with an object and a tingling-sensation in the hands. The frequency of each is shown in Figure 56 and is elaborated on below. Finally, two participants’ responses were regarded as unambiguously indicating no sense of touch whatsoever, as illustrated in the following response: *“It was strange to stretch out your hand and see that you’re touching something, but you still don’t feel anything”*.

With regards to what the current study regards as a touch-sensation, as mentioned, this was divided into two main categories: touch-sensation and tingling-sensation. A sensation was regarded as a touch-sensation if it included any description of touching a physical object, such as the following:

- *“Similarly [sic] to what I wrote in my questionnaire there, I said that the sound that emerges from you touching the blocks, it creates an actual sensation in your hands, you can actually feel as if you are touching the actual blocks due to the sound.”*
- *“It was very cool, and they went down when I rubbed them, and it felt as if I’m really touching something.”*
- *“The faster I rub, the faster the sound goes [sic] and it also, especially when I went very fast, it felt as if I’m rubbing something... touching that surface.”*
- *“...if you would’ve put a fur coat there I wouldn’t know which hand was feeling a fur coat and which hand was feeling a block.”*

Some of the remarks also indicated a contradicting experience where participants described being consciously aware of the lack of any physical objects, but still experiencing a touch-sensation:

- *“In your brain you know it isn’t there, but kind of if I’m there it feels... understand? It really feels real.”*
- *“If I rubbed the blocks... your mind almost tricks you into believing that you are actually... touching something. So, it feels as if you’re touching something, but it doesn’t. Does that make sense?”*
- *“Like, if you strap on the little thing and you, well for me it’s my left hand, and I rub the back of my hand on something, it actually feels like my hand is expecting to feel*

something if that makes sense. So, it kind of becomes more sensitive in a sense and it makes me feel like it feels something, but it's not actually there.”

This awareness of the lack of physical stimuli indicates a robustness in the illusion, since participants were aware of their tactile sensations being illusory, but enacted a willing suspension of disbelief to continue to experiencing them (Magnenat-Thalmann et al. 2005), which is discussed in detail in section 5.2.4.3.4. During the interviews, 11 participants (n = 18) who experienced a sense of touch noted this type of awareness of the illusion. During the non-expert focus group, all six participants agreed to have experienced a sense of touch despite knowing that there was no physical stimuli present.

The second type of sensation described is characterised by participants noting a “tingling-sensation” in their hands, such as described in the following remarks and exchanges:

- **Researcher:** *“In which rooms did what you experience come closest to actual touch?”*
Participant: *“Room 5 and 2. Room 5 because of the blackboard feeling and 2 because it felt tingly in my hand.”*
Researcher: *“Can you elaborate on this tingly feeling? What sort of real-world feeling does it remind you of?”*
Participant: *“Like if you have pins and needles in your hand.”*
- *“It felt as if there was almost a sort of pins and needles in my fingers if I felt across the blocks.”*
- *“And the one in the middle being almost like a fur coat, I could actually feel the tingling in my fingers as I went along it.”*

The tingling-sensation was also accompanied by comments regarding the lack of physical stimuli:

- *“It feels as if... I think it’s just because my brain doesn’t quite know what to do with this thing that I can see it’s touching, but it’s not really touching anything. So, it might just be a thing that your head wants to do to try and understand; but it feels warm in my fingertips and a bit pins-and-needles-like [sic] when I touch those blocks.”*
- **Researcher:** *“Anything else in terms of your sense of touch?”*
Participant: *“Uhm, there was something. I wasn’t quite sure whether it’s... it didn’t happen often, but sometimes when I was rubbing some of the objects, especially like the first one, I kind of get this... I had a feeling [gesture of rubbing hands together] in my actual hands. Like a kind of tingling feeling when I touch the objects. And then I tried replicating that by just waving my hand and that didn’t... it didn’t happen”*

Researcher: “So it was only when you rubbed the blocks?”

Participant: “It was only when I... any form of, with the fingers, with the hand... [sic] with the palm or back of my hand for specific things, for when it made sense, like with the carpet, and then the sound of the carpet, I think everything added together and maybe potentially warped my brain and thinking ‘this could potentially be something’ [sic] and that initiating a reaction of some sort.”

It should be noted that the second participant above has previous development experience in VR. As indicated in Figure 56, all participants who noted tactile sensations experienced either one or both of these two types of tactile sensations. A smaller number of participants who noted a touch- and/or tingling-sensation also noted a few other types of sensations which do not clearly fall into these two categories. Of these other sensations, the most common was a shudder-sensation, which was experienced by 4 participants (n = 18), of which two examples are listed below:

- “They all felt like blackboard, like touching a blackboard, and it was quite an intense sensation, it made me want to pull my hand away. So, it was very hectic, I hate scratching a blackboard; it was that feeling.”
- “With this hand I’m like ‘ahh, itchy’ [sic], after I rubbed with [that hand]. Now I’m like ‘it feels wrong’, I have to scratch now [gesture of scratching hand]. Like an after-effect, I guess?”, “Afterwards, I was like, ‘now I want to rub my hand, like, scratch or something’.”, “It’s almost like you experience a texture which is kind of new to you, like, touch it and then a shudder-effect almost.”

Apart from this sensation, the following 4 participants (n = 18) each experienced a sensation that was only described by them:

- “Room 8 gives... it makes these nice warm hands when I touch these things [sic].”
- [while interacting with the prototype, this participant repeatedly pulled their hand away when making contact with the blocks and verbally expresses displeasure] “My immediate response when touching the black block, the sandpaper, was like, ‘you can’t touch that’. It felt like I was going to hurt my hand.”, “I don’t think I could rub the whole block once, because every time it was like ‘mmhmm, no’ [sic].”
- “It feels like, I don’t know, that sound makes me want to scratch. So, it feels a bit as if it makes my fingers itch.”, “It feels to me as if there should be... almost as if I was actually scratching wood and now I want to get the things out from under my nails. It makes my fingers itch.”

- *“But I think for just over 50% I could actually feel... either my brain telling my hand to slow down and to... you know, you can't go fast, because there's some resistance to it.”*

With regards to the responses to the first key question, “In which room would you say what you experienced came closest to actual touch”, the results are shown in Figure 57. Two notable observations from these results relate to room 1 and 3, with room 1 being the modal value and room 3 being the only room that was not listed by any participants as creating the closest touch-sensation.

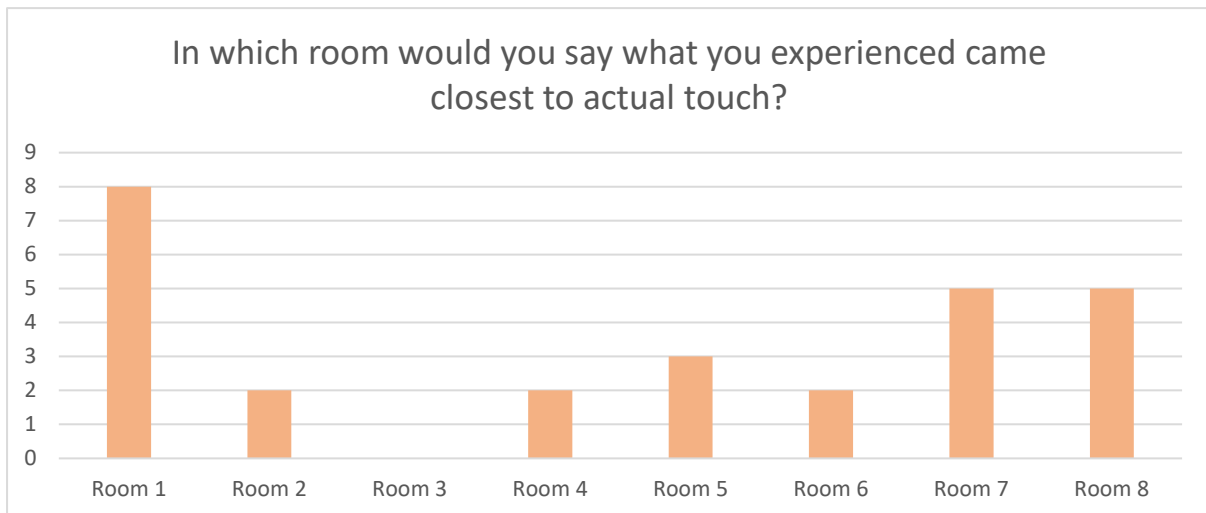


Figure 57: The occurrence of each room in the response to the first key question (it should be noted that participants were allowed to choose more than one room)

However, not only was room 1 the modal value, but it was also the answer which occurred most often on its own, with six participants ($n = 18$) only noting room 1 as creating the closest touch-sensation. It can thus be safely ascertained that room 1 was the most effective in creating an illusory tactile sensation. This is shown in Table 3 below, which summarises the responses of each participant who noted a tactile sensation ($n = 18$) by only noting the room number(s) each participant listed in their answer.

The lack of occurrences for room 3 was confirmed by participants’ descriptions of sensory experiences in that room, such as the following:

- *“I remember thinking that it all just... I couldn't relate the sound that I was hearing when I touched the block to anything that I knew and so I didn't really... I didn't really feel anything in my hand as I would with the other rooms.”*
- *“I think they were very electronic-sounding blocks. It felt very jarring and I couldn't really associate it with touching something else.”*

The selections of room 1 as the most effective and room 3 as the least effective also aligns with the causes of the illusory tactile feedback, which are discussed in section 5.2.3.

Table 3: The room number(s) given by each participant who noted a tactile sensation (n = 18) in response to the first key question: "In which room would you say what you experienced came closest to actual touch?"

Participant number (n = 18)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	x				x	x	x					x			x	x	x	
2				x														x
3																		
4			x										x					
5			x	x												x		
6		x														x		
7									x	x	x			x		x		
8						x		x	x				x					x

This section started with a discussion of how the effectiveness of the prototype was to be evaluated, followed by a method of grouping participants based on their illusory tactile experiences or lack thereof. The effectiveness of the prototype was then discussed by comparing these groupings and investigating the quantitative and qualitative data that directly address the effectiveness of the prototype in achieving its goal. The prototype was found to be effective in inducing illusory tactile sensations for a high percentage of users involved with the usability tests with the types of sensations broadly falling under two categories: the sensation of “touching” a virtual object and a tingling sensation resulting from “touching” virtual objects. The illusion was also found to be robust enough for participants to continue experiencing illusory sensations after consciously noting the absence of physical objects that should be able to induce these sensations. The grouping of participants based on their illusory tactile sensations, or lack thereof, is used for the remainder of this chapter to discuss the underlying causes of these sensations in participants who experienced them.

Having discussed the effectiveness of the prototype in creating a variety of illusory sensations, the next section discusses the mappings between different senses, specifically that between audio and tactile.

5.2.3.2 The mapping between audio and tactile

Before discussing the mapping of information between senses, the current section first distinguishes between the main goal of the study, illusory sensations, and information mapping. As discussed in section 4.2.2.4, the prototype utilised certain properties that can be intuitively mapped between different sensory modalities, specifically between the audio and tactile modality (Hoggan & Brewster 2007; Eitan & Rothschild 2011). These properties were as follows:

- **Volume/intensity:** higher hand-velocity and block displacement always led to higher volumes for sounds being played.
- **Rhythm/pitch:** the abstract audio strategies provided different methods for changing the audio pitch to correspond with hand movement.
- **Timbre/roughness:** different blocks used different audio recordings or synthesised waveforms, which were expected to correspond to different “textures”.
- **Spatial location:** the location of the sound in virtual 3D space always stemmed from the position of the participant’s hand as it touched the block.

These properties were used because the use of cross-modal properties was expected to create stronger cross-modal mappings, leading to stronger perceptions of tactile feedback. However, it is important to note that cross-modally mapping information from one sense to another is not the same as an illusory sensation, as it does not necessarily create an actual sensation in that sense. Thus, a cross-modal transfer of information does not imply a touch-sensation, as data from the usability tests also show, but an illusory tactile sensation is regarded as implying a successful cross-modal transfer, which is elaborated on in section 5.2.4.3.1. In the absence of an illusory sensation, descriptions of cross-modal mappings confirmed the effectiveness of transferring information from the audio to the tactile modality, in line with the findings of Hoggan and Brewster (2007).

As discussed in section 4.2.2.6, the first room in the prototype was the only room to include a visual texture on each block, which corresponded to the sound it produced. For this reason, participants could easily map the audio from the blocks to corresponding real-world textures:

- *“Firstly, realised that the blocks had three different colours and I remember looking closely at the one with the black surface and it reminded me of like a sandpaper sort of*

texture and when I rubbed my hand on top of it, it didn't feel as coarse and rough as sandpaper.”

(It should be noted that the first participant had incorrectly remembered the number of blocks in the first room.)

- *“And then [the second block] had a more carpet-looking texture and the sound of it also sounded, if I had to rub my hands on it, it also did sound similar to what I expected from a carpet kind-of block.”*

Although the audio for the second block was created using a wool jersey, participants tended to describe the texture as a “*carpet texture*”: out of 23 participants, 11 participants specifically referred to it as having a “*carpet texture*”, one participant simply referred to it as being “*fabric*”, and 11 participants did not refer to any textural qualities of that particular block. This is considered to be a valid cross-modal mapping for the current study since they are both made from similar materials and have a similar texture. Thus, the effectiveness of the first room in creating cross-modal mappings of texture information is not discussed, as participants indicated a strong preference for visual information when inferring textural details about the block, which was not the focus of the current study. The remainder of the current section thus focuses on the blocks in the other rooms and their effectiveness in letting participants cross-modally map texture information.

With regards to the type of sounds being played, all participants ($n = 23$) except two noted the presence of the abstract sounds during the interviews when discussing their sensory experiences between rooms. When describing these sounds, participants used a variety of terms, such as “*digital sounds*”, “*electronic sounds*”, “*beeping sounds*”, “*techno*”, “*sci-fi sounds*”, “*non-real-world sounds*”, “*unnatural*”, “*video game sounds*”, “*futuristic*”, “*alien kind of sound*”, “*8 bit sound*”, “*out-of-this-world kind of sound*”, “*computer sounds*”, and “*technological sound*”. With regards to the tonal abstract sound, four participants also compared the sound to music, which was undesirable, as discussed in section 4.2.2.4.3, for example:

- **Researcher:** “*How would you describe [these sounds]?*”
- **Participant:** “*It plays computer music.*”

Video recordings also show that a number of participants laughed while interacting with the tonal abstract sounds and some participants described them as “*entertaining*”. Thus, participants easily drew a distinction between sounds they could associate with real-world objects, which are referred to, in the words of one participant, as *organic sounds*, and sounds they could not, which are referred to as *abstract sounds*. In terms of identifying sounds as either organic or abstract, participants noted three determining factors.

The first of these, as already mentioned, was the fact that participants could not associate with real-world objects or events. This was exemplified by remarks such as:

- “[the sound] felt like it wouldn’t always fit as if it would have been in a natural environment.”
- “...coming from the sandpaper and the carpet, it was like ‘oh, this block looks like nothing, so not sure what it’s going to sound like’ and then it sounds like something that I have no picture for.”

This disconnect thus prevented participants from experiencing the sounds as believable events which stem from a touch-interaction, as is discussed in-depth in section 5.2.4.3. The second of these factors, also mentioned above, was when participants experienced the sounds as “musical”. The fact that the blocks produced sounds that were recognisable as having musical qualities was always perceived as being disconnected from a touch-interaction with a physical object, as described by the following comment: “Some of it was very realistic and some it was not at all. Especially those which made those very scratchy sounds, it isn’t... it just feels funny. It almost feels like a... DJ board [sic] or something that you’re rubbing across. Like, I don’t what you call it, a synth board? [sic]”. This description of an interaction with an object that plays back a piece of audio rather than an object which “naturally” produces audio feedback from being rubbed was similar to that of another participant, albeit not in reference to musical sounds: “...doesn’t feel as real, doesn’t feel as immersed, doesn’t feel like I’m actually feeling something or actually feeling the block per se. Feels more like I’m, I suppose, pushing a button.”

The third factor, noted by three participants, was the high pitch of the sounds produced by some of the abstract sounds, for example: “The one thing I’m picking up now, I don’t know if it’s happened with previous rooms, but as you pull them down, there they go all the way down, but the frequency of the sound becomes more electronic as you push them down. It becomes high-pitched.” It is also worthy to note that participants who did not mention the abstract sounds or who experienced a sense of touch while interacting with blocks that produced these sounds often moved their hands slowly or did not press the blocks down far enough either for the atonal strategy sounds to be pitch-bent noticeably high or for the tonal strategy blocks to play notes in the higher octaves. Thus, the high pitch of the abstract strategies played a role in establishing the sounds as not organically stemming from a physical object. Triangulated data from interviews and observations suggest that this effect could be reduced by limiting the octave range to two octaves (in this case, starting from C two octaves below middle C).

Although participants drew a distinction between organic and abstract sounds, in some instances the abstract sounds or combination of both abstract and organic were described as various types of real-world objects, as illustrated by the following remarks in reference to rooms other than the first room:

- *“One of the blocks felt like it was blackboard, for me. I touched it and then I pulled away because it felt like... didn't want to touch it for longer.”*
- *“There was one block that had white on it and it sounded like you're touching sand and it also looked like you're touching sand, because the block's colour was almost that colour, a whitish brown colour.”*
- *“...what did stand out a lot for me is the second block here, my hands feel like they're full of static electricity when I run along, very static-like.”*
- *“[this block is] very similar to the previous one. It's got a more... wooden sort of sound to it.”*
- *“So, the block on the far left is like this... ribbed kind of feeling, like a surface with lots of little bumps on it. And the one in the middle being almost like a fur coat, I could actually feel the tingling in my fingers as I went along it. And the one on the right sort of a leathery sound? If you go quickly, like that whole feeling, and it... yeah, definitely could feel something there.”*

It should be restated at this point that none of the textures being described above, such as blackboard or sand, were recorded for the prototype; all of these sounds were the results of various combinations of the two recorded sounds, sandpaper and wool jersey, and various abstract sounds. Of the five textures described above, the most frequently described was that of static electricity, which was noted by seven participants ($n = 18$). It must also be noted that the blocks being described as “looking like sand” by the second participant above had a plain grey texture with no extra visual roughness, although it is possible that the perceived texture of the block was influenced by the screen door effect present in the headset which could add a perceived level of visual roughness (Desai et al. 2014).

In the cases where participants did not compare the textures of the blocks to real-world textures ($n = 23$), they still relied on texture descriptors to describe the different blocks:

- *“And the sound sometimes would be more scratchy than softer [sic], then you'd feel like you're touching a rough surface over a smooth surface.”*
- *“...if I were to imagine how this surface would feel compared to room 2 it's... not smooth. I don't know how else to describe it. It's less smooth than the room before it.”*

In terms of broad textural descriptions, the three textures that were described most often were “rough”, “soft”, and “smooth”. It is expected that the visual textures of the blocks, i.e. the sandpaper- and wool-texture in the first room and plain coloured textures in the other rooms, would have played a role in influencing this selection of textures when describing all textural perceptions, as illustrated in the following remark: *“I think some of the blocks also looked smoother than the other blocks. If it’s only one solid colour, then it looked smoother than blocks that had little pieces of colour in it”*. However, this would only account for differences between the blocks in the first room and other rooms, not for differences between all other rooms than the first. Furthermore, other remarks indicated that, while the visual textures did play a role in the perception of a texture, it was not the only influence:

- **Researcher:** *“What would you say is the reason for defaulting to textural adjectives when describing the blocks?”*
- **P1:** *“I don’t know. It sounds rough or it sounds smooth, I can’t think of any other way to describe them.”*
- **Researcher:** *“So is that just the best way you can think of to describe them?”*
- **P1:** *“Yeah, because it’s to do with the texture of the thing. There’s no point in trying to describe the texture of the thing without using those words.”*
- **P2:** *“Also, they didn’t look like anything after the first room.”*
- **P1:** *“And it’s not like I can say the block looked... sound blue... It sounded like a rough block; it’s the most accurate way I can describe it.”*

It should be noted that participant 1 above was one of the two participants who did not note experiencing any tactile sensations. Both participants in this “no-tactile sensation” category, however, noted perceptions that are indicative of effective cross-modal mapping during their interviews:

- *“I get a sense of the texture of what the thing should be, but obviously I don’t feel anything. So you can sort of hear if something sounds like it’s rougher than something else, so if you had to ask... if you had to put a bunch of these in a row and ask me which one sounds like it’s the most abrasive or which one sounds the smoothest, I think I could probably pick them out based on the sounds.”*
- *“It’s kind of like, I can imagine if I were to literally physically feel the block then it would feel the way I’m describing it, so it would feel rough or it would feel smooth or something like that. So, I can imagine what it would feel like, but I don’t actually feel it.”*
- *“With [room 5, block 2] it was as if the sound is interrupted, like there is a bad connection, but with the others it was a nice clear sound. It feels as if, the sound that you feel when rubbing something rough.”*

Thus, the use of sound was an effective tool in conveying textural information, both in the presence and absence of illusory tactile sensations. With regards to the types of sounds and the mappings to different textures, as expected, the recording using sandpaper was perceived as rough, while the recording using wool was perceived as soft, for example: *“The left block [in room 1] was rough and the right one was like fabric, right? So yeah, I got a bit of that feeling that... the sound contributed, like, ‘ok, it feels a bit harder and this one feels soft’. It sounded very natural”*.

Examining the details of the mapping between abstract sounds and different textures becomes problematic, since the prototype contained many combinations of organic and abstract sounds, which, since the goal of the current study was not to study these mappings in-depth, were not explored in-depth per block. Furthermore, since the sounds changed depending on how participants interacted with the blocks, their perception was also often highly individualised, as illustrated by the following remarks, each of which describes the same room (room 7):

- *“So, these first two feel quite a bit like smooth wood, like little bit of a grain and the occasional little bump and that. Second two sound a little bit like the ocean.”*
- *“The blocks, if you rub them, it feels like rubbing your hands on a carpet. Not super soft, but comfortable.”*
- *“Room 7 and 8 were similar, they both were like rough blocks. Room 7 was less so than 8, in terms of the experience seemed like sandpaper, but not as powerful as the first one because the blocks didn't have the look of sandpaper.”*

For the purposes of the current study, the first participant’s perception of the last two blocks in room 7 sounding *“like the ocean”* was not regarded as a description of a texture, but rather as an undesirable sound that the participant could not map to a texture. This discrepancy between texture perceptions can be partially explained by differences in the way participants interacted with the blocks, for example, observation data show that the second participant above rubbed the blocks very lightly, not pushing them down far, whereas the third participant pushed blocks down further while rubbing them, thus creating higher-pitched sounds. However, due to this type of discrepancy occurring frequently when discussing differences between blocks and the fact that an in-depth collection of data specifically relating to the textural differences between all 28 blocks was not a priority during data collection, the exact mappings between different types of sounds and their textural equivalents are not discussed further at this point.

What can be asserted with certainty, though, is the fact that participants experienced all blocks as having different textural qualities and that, in the absence of visual textures, participants relied on sound cues to discern textural differences between blocks, as illustrated by the following remarks:

- *“So, it felt really real in terms of, I could not (emphasis) feel a different texture, but it felt like it could have been a different texture because of the different sounds each block was making.”*
- **Researcher:** *“If you had to describe the ‘digital’ sounds as having specific textures, would you be able to associate those sounds with some sort of texture?”*
P1: *“I think it depends on the sounds. I think it's definitely more difficult to guess what this digital-sounding thing would feel like, but if you compare them with each other, again I'm coming back to rough vs smooth...”*
P2: *“Yeah, if you compare them.”*
P1: *“...some of the digital sounds sound more rough than others, I don't know how else to describe it, but... what I sort of end up doing is I try to imagine what it would look like, some of them, if I were to imagine them existing in the real world, would definitely be... they would have different textures.”*

Furthermore, participants used the audio cues to make sense of the blocks as physical objects and relate them to objects in the real world, as illustrated by the following:

- **Researcher:** *“Another thing that was mentioned was the ‘digital’ sounds. What was the effect of that on your sense of being there?”*
P1: *“I think it kind of... not ruined it, but it did break it a little for me [sic], because it wasn't what I expected when I rubbed the block. It's like, coming from the sandpaper and the carpet, it was like 'oh, this block looks like nothing, so not sure what it's going to sound like' and then it sounds like something that I have no picture for. So, didn't really make it any more real to me, probably made it a little bit less real.”*
P2: *“I think that's part of the reason we can only remember the sandpaper, the blackboard, and... because some of the sounds we couldn't correlate them to anything that we know.”*
- *“...if you were to use these types of audio cues inside a game, I think it will be very effective in the sense that it's easier for users to understand what that thing sounds like or sort-of feel like without having to physically feel the object.”*

Thus, sound helped participants identify textural and physical properties and effectively map audio information to tactile information. When used on their own, the abstract sounds

tended to be ineffective in inducing illusory tactile sensations, as illustrated by the low numbers for room 2 and 3 in response to the second key question as shown in Figure 57. This was attributed to three main reasons: the fact that participants had difficulty associating these sounds with real-world objects and events, the perceived musical quality of some of these sounds, and the high pitch of some of the sounds. Despite the relative ineffectiveness of single abstract sound strategies on their own, they were found to be useful in combination with other abstract as well as organic strategies as they created perceived textures that were not recorded for the current study. However, due to the highly individualised nature of this perception, the precise combination of audio strategies and the resulting perceived textures were not investigated in-depth. Furthermore, participants who did not experience illusory tactile sensations could still effectively map audio to tactile, such as noting which sounds are “rough” or “smooth”, which is in line with findings by (Hoggan & Brewster 2007).

The next section discusses another main focus of the current research: the factors that were found to help or deter participants in experiencing illusory haptic feedback.

5.2.4 Causes of illusory tactile sensations

This section discusses all the causes of intersensory illusions, focusing on illusory tactile sensations, described by participants. Participants’ responses are first grouped and discussed. The emerging themes of these causes are then organised into two main groups which most causes were found to fall under.

5.2.4.1 Factors that caused illusory touch

In order to group and assess the role that the various parts of the prototype played in inducing illusory tactile feedback, the results for the second key question, “*Can you elaborate on why that room’s touch experience felt more real than the others?*”, were divided into two groups which characterised the two main causes listed by participants as the main influence on their illusory sense of touch: visual- and audio-feedback. Similar to the approach taken in section 5.2.3.1 and illustrated in Figure 57 to assess which room was the most effective in creating illusory tactile feedback, only the responses from participants that reported illusory tactile feedback were included in this assessment. The results of this question are shown in Table 4 and Figure 58 below, with Table 4 listing the responses from each participant who noted a tactile sensation (n = 18) along with the corresponding room number and Figure 58 providing an overview of the occurrence of each category of motivation given by participants. For both of these, the motivations are denoted by the following: visual (V), audio (A), both (B), and other (O). It should be restated that participants were allowed to choose more than

one room as their answer to the previous key question: “In which room would you say what you experienced came closest to actual touch”.

Table 4: The room number(s) and motivation given by each participant who noted a tactile sensation (n = 18) in response to the second key question: "Can you elaborate on why that room's touch experience felt more real than the others?"

Participant number (n = 18)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	V				B	A	B					B			V	A	V	
2				A														A
3																		
4			A										A					
5			A	A												A		
6		V														A		
7								V	B	V			B		A			
8						A		O	V				A					A

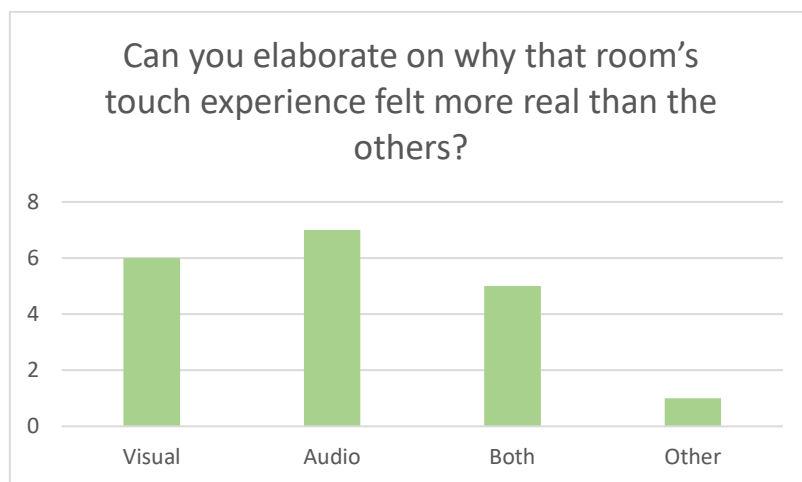


Figure 58: A broad overview of participants' responses to the second key question, grouped into two general categories

Responses were grouped under the visual category if the answer to the second key question only referred to the participant's description of their visual experience, for example, "*The rooms where there was also a texture on the plank, was it room 1? That really contributed to feeling. The rest of the rooms I would... the illusion of texture tricked my brain a bit [sic]*", while the same applied for the audio category, for example, "*[The blocks in those rooms] came closest to reality, because those sound are sounds that, I'd say that I've heard before and can relate those sounds to certain objects*". Responses fell into the "both" category if the participant noted the combination of both audio and visual as the main contributor to their sense of touch, for example, "*I wouldn't necessarily say it's primarily because of the way it looks, but my expectation was firstly from a visual sense before the audio played, so I think it's more in the sense the two senses connected well together was the reason it felt more real [sic]*".

Finally, one participant did not attribute their touch-sensation to either the visual or audio representation of the blocks or environment, but rather to what would normally be thought of as an undesirable mismatch between their interactions and the result from the prototype. As mentioned, the Leap Motion has a limited tracking range and if one's hands go out of this tracking range in real life, the virtual hand-instances are destroyed. While this participant was reading the instructions, they tried to rub the blocks, which were out their visual field of view and the Leap Motion's tracking space at the time, which prevented them from being able to do both at the same time.

Contrary to what would normally be expected, this mismatch between their expectation and what was delivered by the prototype caused this participant to experience the closest touch-sensation in the last room, as illustrated by their comments: "*All the rooms felt natural, I knew I had to do this and that, but this one, because suddenly there were instructions, at that point I was so immersed, when I touched [the block] again, I was like 'oh' [surprised]. Underlyingly [sic] I thought I would just be able to touch it, so because that's what I thought it felt more realistic*". Because this participant's response was the only one that did not specifically allude to the effectiveness of the feedback in either the visual- or audio-modality, their response could not be grouped in either category.

These results further point to the effectiveness of audio in inducing illusory tactile sensations. An example of this is found in the results of room 1: of the eight participants that noted room 1 as the most effective or one of the most effective rooms in creating illusory tactile feedback, three participants attributed this only to visual feedback, two to audio, and three to a combination of both. Thus, although room 1 was the only room with a visual component, a substantial number of participants attributed their perceived tactile sensation to the audio created by the blocks. Furthermore, audio on its own was listed most often as the cause of the

most effective illusory tactile sensations, which is expected to be largely due to the absence of unique visual textures for all rooms except the first, in other words, as one participant stated, the fact that “*they didn't look like anything after the first room*”.

These responses, however, are only a broad overview which focus on the visual and audio modality. As discussed in the next section, participants went on to describe a number of additional factors which had a positive or negative influence on their illusory sensation of touch. The next section thus investigates themes that emerged from participants' responses from interviews and the following-up on these themes during focus groups in more depth to identify the main themes that were cited as having an influence on participants' illusory sensation of touch.

5.2.4.2 Involvement and presence

As discussed in section 2.3.2.2, the current study distinguishes between presence and involvement as events that are not mutually inclusive, but have been known to have a correlative effect, since the amount of attentional resources that a participant devotes to their experience encourages an enhanced suspension of disbelief (Bystrom, Barfield & Hendrix 1999; Sheridan 2000; Lessiter et al. 2001), which is expected to have a positive influence on presence (Witmer & Singer 1998; Lessiter et al. 2001). This was supported by two comments from one participant during their interview and focus group respectively:

- “*If you get distracted by some other things, I mean such things [a sense of touch] you will not feel, because overall you do know that this is a game, you do know that this is impossible, but if you do **submit yourself** to the game you start feeling everything.*”
- “*...you only experience a sense of touch if only you allow the game **consume you**, like [another participant] said before. If you are **distracted** by other things or thinking about other things, you won't feel anything, because your mind will tell you, 'look, this isn't reality'. For me if you're consumed by the game and you love what you are doing and it's something interesting to you, only then can you feel a sense of touch.*”

Because of this relationship, these two factors are discussed in tandem, starting with involvement.

5.2.4.2.1 Involvement

As the previous comments regarding presence, involvement, and suspension of disbelief above show, the participant regarded their attention on the experience as a direct influence on their sense of touch. This direct relationship between involvement and a sense of touch was also noted by other participants. Two participants noted that the sounds that they perceived

as unpleasant had a better experience on their sense of touch, because they focused more of their attentional resources on the blocks that produced these sounds:

- “[the sounds] almost make you cringe. It actually ‘put me into it’ more, if I can put it like that.”, “the sound that is cringe-y [sic], like I said, it hits a nerve and because of that it makes it feel more realistic.”
- “For me, in many cases, the unpleasant sensations, rather than the pleasant sensations, had a bigger impact.”

Another participant, while noting a better touch-experience with the softer rather than the louder, harsher sounds, also noted a direct relationship between their attentional engagement and their touch-sensation: “I found that, definitely with the softer sounds, I could relate a lot more, I could definitely feel a lot more, get more engaged, whereas with some of the harder, louder sounds, if I can maybe call it that, the harsher sounds, it broke it a bit for me [sic], didn't really feel as much”.

Another factor which influenced involvement was the integrated use of more than one sensory modality to describe an object, which is expected to not only have an additive effect on intersensory influence, but rather an effect which is greater than the sum of the results from the senses involved (Bresciani, Dammeier & Ernst 2008). The use of corresponding feedback across multiple sensory modalities was found to focus participants' attention on the blocks, as illustrated by the following explanation as to why a participant did not focus on the room, but rather on the blocks: “...maybe it's because more senses are linked towards the blocks [sic], so when you touch the blocks you hear a sound. Looking at the room there's nothing really happening”. This combined effect was also noted by another participant: “I felt very immersed in the environment, it was very nice for me to see that if I touch the block something happens and there is also a sound as I rub it, and then the sounds differ depending on how I rub it. It involved me very much in the environment [sic]”.

This combined effect also offers an explanation as to why room 1 was the most effective in creating illusory tactile feedback, since participants could focus on feedback in more than one modality and could match the different feedback in the context of the block, as illustrated by the following remarks:

- “So, with the sandpaper it felt rough and coarse, in room 1 on the left, and the block on the right that looked like carpet felt more like carpet than it would've if it didn't. If it was just a flat block it wouldn't have been as effective and if the sound wasn't there it also wouldn't have been as effective.”

- *“...the one block had a carpet texture and the other one... it looked more realistic, which engaged more senses, as opposed to the other blocks, which were just a colour.”*

This is also shown in one instance where a participant did not perceive the block as a plain flat surface, but attributed a sand-texture to it, possibly due to the screen-door effect, as already mentioned. This participant noted that the block looked like sand and also sounded like sand when you touch it, which created a sensation that was *“...almost like you can feel it when you touch the blocks”*.

Another less-frequently discussed factor that influenced participants’ use of attentional resources was their “cognitive strategy”, i.e. which sensory modality participants relied on most to gather sensory information (Lecuyer, Cuquillart & Coiffet 2001). Two participants (participant 1 and 2 below) explicitly discussed their cognitive strategy during the non-expert focus group while discussing why they paid more attention to the colour-differences between the rooms than two of the other participants (participant 3 and 4 below):

- **Researcher:** *“Can you think of why some of you noticed colour first?”*
- **P1:** *“For me colour is very important, even in my presentations in class I like it to be colourful. That’s something that stimulates me, first thing, even if I walk into a room, colour would be something that I pick up first.”*
- **P2:** *“Colour, I agree. I think that’s why we tended to pick that up first, because in general we’re people that react to colour. Whereas somebody that doesn’t react to colour probably won’t get that same emotional attachment to each colour in each room.”*
- **P3:** *“Yeah, I’m not a person like that. It was like, colours don’t...”*
- **P4:** *“I was just like: ‘I’m here for the blocks.’”*

These distinctions also aligned with the participants’ discussions during their interviews. Participants 1 and 2 specifically noted the colours of the rooms while describing their experience whereas participants 3 and 4 broadly discussed a range of factors, such as the visual textures of the blocks and the sounds. It should be noted that participant 4 was one of the participants that fell into the “unsure/contradicting” category, thus their feedback is not focused on. In response to the summary question, *“Is there anything else that we haven’t discussed that you would like to talk about?”*, both participants 1 and 2 mentioned the room itself while participant 3 did not:

- **P1:** *“The soft colours that you used in the room, I like it, because it isn’t too visually straining. I didn’t feel nauseous or anything during the whole experience and it’s a calming feeling, maybe because there isn’t too much around you. It’s not cluttered, so it*

also makes the whole process of moving through this virtual reality system more comfortable.”

- **P2:** *“I think the room itself, I would look around and it almost looked like the lining on the bottom of the walls and things like that, the details stuck out for me. I would even look at the block and I would see how the wood almost looks like real wood. So, the small details really stuck out for me in the rooms, because that's what I would look for. So that was a big plus to make it feel more realistic.”*

Researcher: *“Would you say that it had a positive effect on your experience?”*

P2: *“Yes, definitely. Almost makes you feel more comfortable.”*

- **P3:** *“Just kind of how, I don't know if it's about the sound, but the sound on certain blocks stood out for me, certain sounds make it feel more real, or sound more real.”*

Both participants 1 and 2 listed being relaxed and comfortable as contributing to their experience of touch, with participant 1 stating that they felt more of a touch-sensation when they understood their environment better and felt more comfortable in their environment and participant 2 citing the colour of the wall in room 7 as having a relaxing quality and being relatable to their everyday environment.

The same occurred for some participants in terms of sounds, i.e. that their cognitive strategy seemed to be centred on the sounds rather than the visuals. For example, two participants who noted the audio as the main influence on their touch-sensation both displayed a narrow focus on the audio feedback from the prototype. One of these participants, when asked about their sensory experiences from the first room noted: *“...honestly the only thing that changed from room to room for me was the sounds. Maybe I was too glued on the sounds, I didn't pay attention to any other thing; I was just feeling the objects, just moving them up and down”*.

The other participant, when asked the same question for each room, only mentioned the visuals once when they asked whether the colours used for the blocks and the walls were the same. Thus, both of these participants were, to use the terminology of Lecuyer, Cuquillart and Coiffet (2001), “sonically oriented” (Lecuyer, Cuquillart & Coiffet 2001). As discussed above, an increase in involvement is expected to positively correlate with presence, which is discussed next.

5.2.4.2.2 Presence

As discussed in section 2.3.2.2, Heeter and Allbritton (2015) list four dimensions of presence in VR that relate to different aspects and causes of a VR experience (Heeter & Allbritton 2015):

- **Personal presence:** comes from the user's perception of their body in VR as well as being able to control it.
- **Social presence:** comes from other social beings in the VE who react to the user's actions.
- **Environmental presence:** comes from the reaction of the virtual environments and objects to the user's actions.
- **Embodied presence:** comes from the user paying attention to and reacting to emotions and feelings so as to connect to their sense of self. This concept stems from the notion of "introspection", which refers to being aware of physical sensation, such as temperature or pain, in the real or virtual world.

Three of these dimensions were frequently discussed by participants regarding their experience using the prototype. The only dimension that was not experienced by participants was that of social presence, since the prototype did not contain other social beings that could react to their actions. Since much of the discussion regarding participants' sense of presence and illusory tactile sensations aligns closely with the remaining three of these dimensions, the remainder of this section discusses each of these dimensions in turn.

Personal presence

Since the prototype did not include a virtual representation of any other part of the body than the hands, personal presence most often took the form of a sense of "hand-ownership", i.e. a sense that the virtual hands are "their" hands, as illustrated by remarks such as the following:

- *"The hands were a good touch, it made me feel like those were my real hands that can touch things."*
- *"My overall experience of it... it's strange, because you begin to accept that it's your hands and you begin to accept that you are touching things."*

Apart from this explicit mentioning of hand-ownership, as briefly discussed in section 5.2.1, hand-ownership was also mentioned implicitly by the description of the virtual hand-representation as "my hand", for example: "...it was cool to be able to move [the blocks] with my hands..." or "...I could see my hands and they moved, how my hands moved, that was really cool [sic]". Comments such as these were noteworthy since this way of describing the

virtual representation of participants' hands in the virtual environment did not delineate between their hands in the real world and the corresponding representation in the virtual environment controlled by their real-world hand movements.

It is also worth noting that this was also the case for participants with previous programming or development experience, such as the following two, the first of whom has specifically developed for the Leap Motion before:

- *“[the sound] is a lot softer when I work with my finger than when I use my palm and backhand.”*
- *“As soon as I put it on and I could see my hands and they moved, how my hands moved, that was really cool.”, “so without, just looking at the environment and just looking at my hands and not even touching anything, it felt quite, like, I get that sense of immersion.”*

With regards to what played a role in establishing hand-ownership, participants specifically noted the behavioural realism of the hand. Video- and screen-recording data show that many participants spent some time, often at the start of the usability test, but also while moving through the rooms, examining their hands and making subtle finger-movements, which, due to the approximately 4mm accuracy of the Leap Motion device (Butt et al. 2017), corresponded closely to the movement of their real hands. This was specifically noted by some participants:

- *“...I started pushing the blocks down and playing with it like this and it was cool because it was so realistic, so I felt that everything, I would even turn my hand a bit to see if it would... you know, was exactly the same as it was.”*
- *“There were times I felt that I was there, due to how the virtual hands imitated my own.”*
- *“So, especially the realism of moving your hand and the speed at which you move the hand and how far you push down, all of that made it feel more realistic and so the sense that you got in your hand was more realistic than it would've been otherwise.”*

In other words, participants' proprioceptive sense of the position and movement of their hands and fingers aligned with the visual representation of their virtual hands. With regards to the visual representation of the hand itself, only two participants noted the visual appearance of the virtual hands, noting that it looked unrealistic.

However, both of them still indicated a strong sense of hand-ownership:

- **Researcher:** *“Anything else that we haven’t discussed that you would like to talk about?”*
Participant: *“The hands are real. The hands make me feel like I’m... those are my hands. That’s pretty much it.”*
Researcher: *“So the virtual hands made you feel like those were your hands?”*
Participant: *“Yes, it was a nice touch.”*
Researcher: *“Even though they weren’t realistic?”*
Participant: *“Nah. [sic]”*
- *“You see something that isn’t supposed to look like [the virtual hands], your association with how your hands look is completely different than these black gloves that you have on, and then you feel your own hands and then all of a sudden it’s like ‘oh my word’. You feel real in a world that isn’t real.”, “My overall experience of it... it’s strange, because you begin to accept that it’s your hands and you begin to accept that you are touching things.”*

Since the virtual hands were effective in creating a sense of hand-ownership and since their visual appearance did not prevent participants from experiencing them as their own hands, the current study regards the use of abstract hand-models rather than realistic-looking ones as successful in preventing the issue of the uncanny valley, as discussed in section 4.2.2.2. One less-successful aspect regarding hand-ownership, as already discussed in section 5.2.1, was when the Leap Motion device temporarily lost tracking of the participant’s hand, which caused jittery movements or inversion on the vertical axis and thus a mismatch between their real hand movements and those of the virtual representation, as illustrated by the following from the non-expert focus group:

- **Researcher:** *“Another thing that sometimes gave problems was the behaviour of the virtual hands. Did anyone experience behaviours that didn’t correspond that well to your real hands?”*
- **P1:** *“Sometimes when you tried to scratch, it didn’t...”*
- **P2:** *“Your hand would disappear into the block.”*
- *[general laughter]*
- **P2:** *“That happened to me a couple of times.”*
- **P3:** *“Or it would be inverted.”*
- **P4:** *“Yeah.”*

- **P2:** *“Sometimes when you would switch your hand, sometimes it would feel like your hand is disappearing in the block.”*
- **Researcher:** *“What was the effect of this on your overall experience?”*
- **P2:** *“That again just stated that this is not real. That was the main effect.”*

However, participant 2 and 4 above both noted a strong sense of hand-ownership and an illusory tactile experience during their interviews.

During the expert focus group, one participant also noted the tracking issues:

- *“...every now and then the motion tracking on the hands would get a bit wonky and it would flip upside down and stuff [sic].”*

This participant, however, also noted a strong sense of hand-ownership, but not an illusory tactile experience. Thus, it would seem that, while participants did experience some mismatches between their own hands and the virtual representations, they were still able to maintain a strong sense of hand-ownership which directly aided in the perception of a sense of touch. This sense of hand-ownership is regarded to be a requirement for experiencing illusory tactile feedback due to bilateral nature of touch, which is elaborated on in section 5.2.4.3.1.

Finally, with regards to personal presence, two participants noted the absence of a virtual body during their interviews:

- *“It was strange, at one point I was looking at my hands and then looked down and there were no arms, and I was somewhat surprised, and then looked down and there weren’t any legs or a chair or anything and I found it surprising that these things weren’t there, because it felt as if I was in a different place.”*
- *“It’s a cool experience, but you feel like a ghost or something, because it’s you, but it isn’t you at all. There’s like a disconnect with yourself, almost [sic].”, “...you feel like a ghost. I think it’s also strange, because after a while you’re just a pair of hands.”*

It should be noted that both these participants described experiencing strong hand-ownership and illusory tactile sensations during the usability test. One participant (participant 2 below) also noted a related point during the expert focus group:

- **Researcher:** *“Hypothetically, if we assume that it is possible to create some [real] sense of touch in virtual reality, would you agree that this is important?”*
- **P1:** *“Yes, definitely, that would be important.”*

- **P2:** *“It’s like the difference between sort of being a ghost in the VR that you are in versus actually feeling that you’re a part of it.”*

It should be noted that participant 2 above did not experience any illusory tactile feedback during the usability test but did note a strong sense of hand-ownership. Similar to Leap Motion tracking issues, it seems that the mismatch between one’s sense of their real body and the virtual representation (or in this case the lack thereof), while having a negative influence on their sense of personal presence, did not prevent participants from experiencing a sense of inhabiting a virtual body in a virtual space. As the following remarks show, the sense of personal presence had a positive influence on participants’ experience of illusory tactile sensations:

- *“The hands were a good touch, it made me feel like those were my real hands that can touch things.”*
- *“So, especially the realism of moving your hand and the speed at which you move the hand and how far you push down, all of that made it feel more realistic and so the sense that you got in your hand was more realistic than it would’ve been otherwise.”*
- *“...you begin to accept that it’s your hands and you begin to accept that you are touching things.”*

Environmental presence

The topic of the environment reacting to participants’ actions was mentioned frequently during the open-ended questionnaire question, interviews, and focus groups. Since the main focus of the prototype was on interaction with the blocks, feedback regarding the reaction of the environment and objects tended to focus on this interaction, with a much smaller number of participants noting the interaction with the teleportation mechanism, for example:

- **Participant:** *“What was really cool for me, every time you touched the blue ball [teleport mechanism], that was fun.”*
Researcher: *“How so?”*
Participant: *“The colour changes; I don’t know, it feels as if you have momentum, as if you... every time there is a shift it’s almost like a ‘level up’ [sic].”*

For the blocks, many participants noted a positive reaction toward the environment reacting to their actions:

- *“It was nice to see if I rubbed the blocks something happens and then there’s actually sound when I rub it.”*

- “...if the objects in the game or VR, they don't move... for me it's as good as watching a movie, you're just looking at things, but if you can interact with them it makes it more interesting.”
- “What specifically stood out for me [in room 1] was, because it was my first time in VR, pushing down the block, seeing the instructions; it stood out for me, you know? You don't just read the instructions, but it's actually interactive, kind of. You have to push it down to progress with the instructions.”, “This one, like I said, just in terms of how it was interactive, that was very cool. You have to push it down read further, to actually look through it. So that ‘took me in more’, if that's the right word. Immersed... [sic].”

It should be noted that what the last participant is referring to is the fact that two of the instruction “pages” on the wall in room 1 were semi-obscured by the blocks, due to the size of the instructions in order to make them readable. Participants could easily see the instructions by leaning forward slightly or pushing the block out of the way, which is what this participant did, which they experienced as “*taking them into*” the environment, although it should be noted that this effect was not a conscious design choice on the part of the researcher. While all three of the above participants also experienced an illusory tactile sense, one of the participants who did not also noted that the “interactive nature” of the prototype had a positive effect on their experience:

- “It was fun to hear that, because you don't feel [the blocks], if there is another sense it feels more real. So, it just contributed to the whole experience of feeling something and then there is an effect on it; there is a sound happening there, it's not just air.”

It is important to note that, when asked about their use of the word “*feeling*”, the aforementioned participant explained it to refer to the use of their hands to interact with the block and not to any sensation in their hands. From these, and other, examples, it is clear that the behaviour of the blocks contributed to a sense of environmental presence in two ways: their vertical movement and the sounds they produce. These behaviours helped participants experience themselves as being part of the virtual environment or, in the words of another participant, “*It sort of helps you feel like you're part of that world*”, since, according to that participant, “...it's interacting with stuff [sic], that's what you always do in real life”.

With regards to the influence on illusory tactile sensations, environmental presence mostly contributed by adding a perceived sense of realism:

- **Researcher:** “What was your overall experience during the experiment, especially while rubbing the blocks?”

Participant: *“Super real, as soon as you touch the block, the noise it makes. So, I feel it only made it more real, because that sound didn’t play until you literally touched the block.”*

Researcher: *“In which way is it real to you?”*

Participant: *“It feels as if you’re literally there, it feels like it’s me standing there and literally touching the blocks.”*

- *“...I also think if you... because you touched something and something happened, like, it made a sound, it also makes it feel more real, if that makes sense, because there is a reaction. So even though it isn’t something that you really feel, there is something that happens and that almost made it feel like you’re feeling something.”*
- *“So overall, the touch was, it was amazing to get feedback when you rub the stuff, when you pull it up, when you put it down, it looked real, it felt real.”*

Thus, the fact that the audio feedback and movement of the blocks stemmed from an interaction rather than an arbitrary event, in other words, the fact that participants initiated an action which led to a response rather than passively observing, or, in the words of one participant above, *“watching a movie”*, created a sense that the environment was “real”. However, as section 5.2.4.3 discusses the topic of realism and believability in more detail, this topic is not elaborated further at this point.

Participants also reacted positively to being able to enact a range of interactions on the blocks, even though this was very limited:

- *“I also started to push the blocks up and down from the third room onwards, if I can put it like that, where I noticed that you can actually lift them up and push them down as well. You want to be a bit more interactive, because you feel that you’re starting to know your environment better.”*
- **Participant:** *“I wanted to see if I could make different sounds by going faster and slower and stuff like that, I wanted to sort of test out what I could do.”*
Researcher: *“What did you experience as a result of that?”*
Participant: *“Enjoyment, I guess.”*
- *“Pushing down the block, it’s like it’s on a spring, you push it down and it bounces back and you can sort of bounce it around and stuff, it’s... interacting with stuff [sic], that’s what you always do in real life.”*

One participant, however, noted that they would have wanted to be able to enact a wider range of interactions on the blocks, as expressed by the following exchange:

- **Researcher:** *“Anything else that we haven’t discussed that you would like to talk about?”*
- **Participant:** *“Yeah, I think I mentioned this just now, the blocks, I am able to move them up and down, but not invert them, change their position, put them diagonally [sic], would’ve loved that.”*
- **Researcher:** *“So, you would’ve loved to have a wider range of manipulations for the blocks?”*
- **Participant:** *“Yes, the functionality. But as it is now, it works perfectly fine as well.”*
- **Researcher:** *“Can you elaborate more on why you would like to be able to do more with the blocks?”*
- **Participant:** *“Because the whole idea is to expose me to a virtual environment, like in real life I can take a book, I can flip it upside down, it’s not just up, down, you know? I can open stuff, I can invert it, I can move it diagonally, that kind of thing. In a way I felt it was like a one-way street, so either up or down, and obviously scratching.”*

This desire to interact with the block in a variety of ways once again comes from the participant’s want for a realistic and/or believable environment, which is elaborated on in section 5.2.4.3.

Embodied presence

The last of the four dimensions of presence described by Heeter and Allbritton (2015) is that of an *“introceptive awareness”*, which refers to a *“connection to the self and body (paying attention to present-moment sensations and feelings)”* (Heeter & Allbritton 2015). Since a large part of the current chapter has already discussed a variety of (illusory) sensations at length, including sense of touch, force, and temperature, this section does not reiterate on these sensations. With regards to their physical sensations from using their hands in the real world, four participants noted sensations that can be ascribed to side-effects of motor actions in the real environment (Lecuyer, Cuquillart & Coiffet 2001). The first of these side-effects is that of wind moving over participants’ (real) hands:

- *“I remember that was when I felt [a sense of touch] for the first time, especially when I moved fast, then the wind also goes over [my hand] and then that helps.”*
- *“So, what I noticed: the palm [of my hand] feels like it’s the least in contact with the block; the top of my hand, that feels the most... because it tingles, I feel as if I’m getting*

tingles. But I think it might be from the hair and the air. And then my fingertips as well.”

When asked about the effect of the wind on their experience of touch, the first participant noted that they think “...*the wind helps, it shows that there is actually interaction with my hand*”. This participant also noted that “*the wind, as it touches my hand, becomes part of the environment for me*”. The second of these side-effects, which was only mentioned once in the expert focus group, is the possibility that part of the tingling sensation might have been from participants holding out their hands for prolonged periods of time:

- **P1:** “*One of the blocks felt like it was blackboard, for me. Like, I touched it and then I pulled away because it felt like... didn't want to touch it for longer. And then the other one my fingers started tingling.*”
- **P2:** “*Exactly what you said, yes.*”
- **P3:** “*Maybe just from holding your hand in the air for like 10 minutes.*”
- *[general laughter]*

It should be noted that participant 3 above did not note any illusory tactile sensations. When another participant in the same focus group was asked whether their experience of a tingling sensation could have been from holding their hand out for a prolonged period of time, they replied with: “*I would say it's more like the different types of feedback that I got from the system which is mostly sound and visuals, that notion for my body to expect something, but not necessarily that the expectation was met, if that makes sense*”. Thus, the effect of holding one's hand out for a prolonged period of time was not confirmed as either having or not having an effect on participants' illusory sense of touch. However, since no other participants mentioned this possibility, it suggests that this did not play a significant role in their experiences. Since, this topic was only brought up during the expert focus group, which was the last method of data collection, this topic was not explored further.

With regards to feelings and internal states, five participants specifically noted feelings of relaxation or comfort in certain rooms during the usability test, two of which have already been discussed when discussing involvement:

- “*The soft colours that you used in the room, I like it, because it isn't too visually straining. I didn't feel nauseous or anything during the whole experience and it's a calming feeling...*”
- **Researcher:** “*Would you say that [the visual details of the room] had a positive effect on your experience?*”
Participant 2: “*Yes, definitely. Almost makes you feel more comfortable.*”

- “The dark blue one [room 6], I felt very peaceful in this one. I just felt as if I could sit here all day and rub the blocks.”
- “Ok, this is the white room. Yeah, this one seems more... natural. It's like room 1, but a bit nicer because it's calming in a way.”

As already discussed, the feeling of being relaxed and comfortable had a positive effect on some participants' attentional involvement and sense of touch, which was also supported by another participant's answer to the question as to why a specific room evoked the closest touch-sensation: “From room 4 you feel you are completely integrated with the space; you feel comfortable and you know how the space works”. All but two participants expressed enjoyment after using the prototype, two expressed fatigue, and one participant experienced one room as being smaller, which made them feel “a bit anxious”.

This section started by establishing the relationship between involvement and presence to be used for the purposes of the current study, with involvement having a correlative effect on presence. However, involvement was also found to have a direct influence on some participants' sense of touch during the usability test and two main factors were found to influence this involvement: the integrated use of more than one sensory modality, such as the blocks' visual textures and audio-producing capabilities, and some participants' cognitive strategy being oriented towards either the visual or audio modality.

With regards to a sense of presence, three of Heeter and Allbritton's (2015) four dimensions of presence were often cited by participants as having a direct influence on their sense of being physically located inside the virtual space as well as on their illusory sense of touch. Out of the four dimensions, personal, environmental, social and embodied presence, the only dimension not discussed by participants was that of social presence, since the prototype did not include other social beings. Personal presence took the form of hand-ownership or a sense that the virtual hand representations belonged to participants, i.e. “were their hands”, despite the unrealistic hand models used for virtual representation and lack of a fully represented virtual body. A sense of hand-ownership was often cited as directly contributing to the sense of “being there” as well as to a perceived sense of touch, although participants who did not experience an illusory sense of touch could still experience a sense of hand-ownership.

Discussions about environmental presence were focused on the behaviour of the blocks, specifically on their ability to move and produce sound in response to participants' hand movements. This was found to positively affect illusory tactile sensations by making the environment and blocks seem more “real”/“realistic”, although, as discussed in the next

section, these topics are quite complex and require further investigation. The same held true for the range of interactions that participants were able to enact on the blocks, even though this was limited. Finally, three participants discussed embodied presence by discussing side-effects of motor actions that could potentially influence participants' experiences of illusory tactile sensations, both touch- and tingling-sensations, although evidence suggests that the influence of these side-effects were minimal. Additionally, five participants noted feelings of relaxation or comfort, which directly contributed to their levels of involvement, which in turn contributed to a sense of presence and in one case was noted to directly contribute to a sense of touch.

With participants' experiences of involvement and presence having been discussed, the next section focuses on their experiences of realism and believability with regards to the environment, objects, sounds, etc.

5.2.4.3 Realism and believability

As already discussed in section 5.2.4.1, participants cited a variety of combinations between primarily the visual- or audio-feedback as having the greatest influence on their illusory sense of touch. However, with regards to the specific details as to why either of these had the greatest influence, 14 out of the 18 participants who experienced illusory touch cited either realism or believability as the reason why either sense created this illusory sensation, with nine focusing specifically on realism, for example:

“Can you elaborate on why that room’s touch experience felt more real than the others?”

- *“I think it’s the colour contrasts which made those blocks look real...”*
- *“...the sound when you touch [the block], I must say, it felt more as if it really could be like that. So, you know, the feeling you would get if you rubbed over a block with your hand...”*
- *“It was mainly the textures of those blocks and then also the sounds, so it felt like it made sense, my brain was like 'ok, that looks like carpet, oh, it sounds like carpet', so it kind of made that link.”*
- *“I feel like it was the most realistic room for me, in terms of the colour was something I interact with every day. It’s a basic colour of a wall, if that makes sense.”*

Realism and believability were thus the factors that were brought up most often as having a direct influence on the core focus of the current study. However, the distinction between the two concepts as found in participants' discussions was not always clear, since certain aspects of the prototype, most notably the blocks, were often described as “*realistic*” even though their behaviour, such as hovering in the air and being displaced, was not. During the

interviews, only one participant noted that the blocks hovering in the air was strange to them: “*It was weird to me that [the block] is levitating, but there isn’t really anything that’s holding it, which sort of disconnects from... because it had a very realistic feel and then you have these levitating blocks here...*”. Another instance where unrealistic properties did not prevent believability was the virtual hands, which, as discussed in section 5.2.4.2.2, were enough to effectively create a sense of hand-ownership. As discussed below, both of these virtual representations relied on a suspension of disbelief, internal consistency, and expectation to be perceived as believable.

When participants were confronted with this inconsistency, i.e. noting unrealistic objects and behaviours as realistic, the following exchange took place in the non-expert focus group:

- **Researcher:** “*From the interviews, most of you indicated that [the experience] being realistic or having a sense of realism was important, or at least beneficial. Does everyone agree with this or have a differing viewpoint?*”
- *[everyone agrees]*
- **Researcher:** “*There were some things in the experience which were blatantly unrealistic, for example the teleportation mechanism or the blocks hovering in the air. Did any of these bother any of you while using the system or stick out as unusual?*”
- *[general disagreement]*
- **Researcher:** “*Why do you think this is?*”
- **P1:** “*Well for me the only time when I actually thought about the blocks hovering was when I pushed them up and down.*”
- *[general agreement]*
- **P1:** “*That was the only thing that first struck me [sic] that this is not really real, because a block would be on a table or on a floor, so it won’t be able to move down. You might be able to pick it up.*”
- **P2:** “*I don’t know if this is correct or even appropriate, but I feel like we’re in such a technological era, like even when I game I get so used to it and it feels so real that, although it’s literally impossible for a block to hover, it feels real to me, because, why not? I’m used to it.*”
- **P3:** “*I agree with that, you almost go into the VR, the system, with an open mind and I didn’t mind if I saw blocks hovering because I was like ‘cool, I’m going into this kind of space where things like this are possible’. So, it didn’t seem unrealistic, even though it is unrealistic.*”

As this exchange shows, the participants only paid attention to or decided to note the unrealism when it was pointed out and, in the case of participant 3 above, still experienced these blatantly unrealistic behaviours as “*seeming realistic*”, which clearly points to believability rather than realism, i.e. verisimilitude which refers to a resemblance to (objective) reality. The same topic was also discussed during the expert focus group:

- **Researcher:** “*How important is the experience being realistic for you in a VR context?*”
- **P1:** “*I would say that, if you say realistic in the sense that whatever context you’re being put in is convincing enough for you to believe what is going on, then realism is quite important. So, in the real world I can’t fly, but if the context was designed in a good enough way that I can fly then that would be pretty cool.*”
- **P2:** “*I would say it does depend on the context, maybe I disagree with [participant 1] a little bit, it does depend on the context; if the context is something that’s requiring me to suspend my disbelief then realism is not that important. Whereas if it’s something like, you’re in a room and you’re touching stuff then that would be better if I could actually feel that I was touching those things, as opposed to not.*”
- *[later in the same focus group]*
- **P2:** “*I should just add to what I said, I think even though you’re in a context that doesn’t require things to be completely realistic, the more things react, like [another participant] said, they react the way you expect them to, the more you’ll feel like you’re there, whether or not it’s a place that you would be, on real earth or not.*”

Here participant 1’s description of the experience being “*convincing enough for you to believe what is going on*” clearly describes believability rather than verisimilitude. Participant 2’s description of realism as being context-dependent addresses an issue raised in section 2.3.1.2, which is that of realism regarding non-real-world objects. In other words, VR is able to simulate environments which have no counterpart in reality, which makes the concept of realism as verisimilitude less useful in these contexts. These descriptions also indicate a malleability in participants’ sense of realism, a notion which was also directly confirmed with the expert focus group. Due to the pervasiveness of this type of interchangeability between the concepts of realism and believability during data collection, these concepts are not discussed separately in the current section.

As already mentioned, the data from participants point toward three main factors as having a notable influence on their sense of realism and believability: expectation, internal consistency, and willing suspension of disbelief. The remainder of this section discusses each in the above order; however, as this section illustrates, these factors are not mutually exclusive and influence each other in complex ways.

5.2.4.3.1 Expectation

When referring to objects or environments in the prototype as realistic, the most obvious way to interpret this attribute is having a verisimilitude, which, as mentioned, relies on a comparison with objective reality. For example, one participant noticed that the rooms themselves looked realistic to them insofar as that they resembled real rooms:

- *“I think it was actually quite well detailed in terms of, like for me, I picked up how good the carpet and the lining against the wall looked.”, “I was looking at details and that made it more realistic, so I didn't have one instance where it felt... it took me out of the presence of the virtual reality world.”*

The same applied to the behaviour of the blocks insofar as that they produced sounds when being rubbed, which often corresponded closely to participants' expectations from the real world: *“And then the block in the middle had a more carpet-looking texture and the sound of it also sounded, if I had to rub my hands on it, it also did sound similar to what I expected from a carpet kind-of block [sic]”*. Although it would seem that it should be possible to clearly distinguish between realism and believability by only including attributes and behaviours that meet participants' expectations from the real world, this expectation also applied to physically impossible behaviours, such as the blocks hovering in the air, creating an illusory kinaesthetic feedback:

- **Researcher:** *“Can anyone think of why [they experienced illusory kinaesthetic feedback]?”*
- **Participant:** *“Maybe it's because you're imagining that 'ok, there's a block and I want to push it down' and by doing that it feels like 'ok, obviously if you push something down it wants to come up naturally'. I don't know, maybe.”*
- **Researcher:** *“So, sort of how you would expect it to do in the real world?”*
- **Participant:** *“Yes.”*

It should be pointed out that the above exchange took place during the non-expert focus group after the topic of the unrealistic behaviour of the blocks had already been discussed. Although realism was cited by participants as one of the factors that had the greatest influence on their perception of illusory touch, only one participant noted the blatantly unrealistic behaviour of the blocks many participants experienced touching. While the participant above does seem to rely on some model of behaviour stemming from the real world, i.e. *“if you push something down it wants to come up naturally”*, the expectation of this behaviour also allows for behaviour that is physically impossible, partially due to a willing suspension of disbelief, which is discussed below.

Thus, the expectation of the behaviour of objects is similar to the notion of a lawful response, i.e. one that participants would expect based on their everyday experiences (Zahorik & Jenison 1998): participants expect certain interactions to have certain effects based both on similar experiences from the real world as well as on the perceived internal consistency of the world, which is discussed below. However, the current data align with findings by Biocca, Kim and Choi (2001) and Biocca et al. (2002) that cross-modal analogs do not have to be realistic to be effective (Biocca, Kim & Choi 2001; Biocca et al. 2002) and that participants can experience the link between their interactions and the system outcome as “transparent” after learning how it works in context (Loomis 1992).

It was mentioned in section 5.2.3.2 that the current study regards an illusory tactile sensation to imply a successful cross-modal transfer. To explain why, some examples of participants’ descriptions of illusory sensations are listed and then discussed:

- “...[the sound] linked to that idea of like... I don't often scratch my hand against a blackboard, but it just had that immediate sensation...”, “that 'vvv vvv' [verbal sound effect], that sound, that loud-soft loud-soft, that specifically is what, I think, made the difference in making it feel like static electricity, or pins and needles.”
- “...the [block] on the left had black on top, it almost looked like sandpaper and with the sound when I rubbed it, it fit well.”
- “Think this was the one where the texture almost felt like the texture was different, because it was like a rough... not such a screechy sound [sic], it was more of a rough sound.”
- “...it feels like I'm working with wood if I rub over [the blocks].”

Although these participants did not explicitly draw attention to this aspect, descriptions of tactile experiences were almost always in reference to real-world textures: as discussed in section 5.2.4.1, all participants except one who noted illusory tactile sensations attributed the effectiveness of the closest touch-sensations to either audio- or visual-feedback. Of these, each participant except one noted that the audio- or visual-feedback made some part of their experience seem more real or made it easier to relate the stimuli to real-world textures. The one participant who did not attribute their closest touch-sensation to either the perceived realism or believability of the environment or the relatability to real-world textures simply noted that the blocks which evoked the closest touch-sensation gave them the most “feedback”, because they made them shudder and pull back their hands (although, when asked what real-world equivalent they can compare the texture to, they did note that the blocks in room 4 and 5 reminded them of sandpaper and charcoal respectively).

In other words, participants needed the expectation of a real-world texture in order to experience an illusory tactile sensation. The inverse is also true: when participants could not cross-modally map audio and/or visual information to a possible tactile sensation, they could not experience that sensation. This is illustrated by the following remarks:

- *“The sound, if I remember correctly, reminded me a lot of electricity and I can’t really touch electricity.”*
- *“For the third room I actually didn't experience anything. I remember thinking that it all just... I couldn't relate the sound that I was hearing when I touched the block to anything that I knew and so I didn't really... I didn't really feel anything in my hand as I would with the other rooms.”*
- *“So, I think they were kind of very electronic, was there an 8-bit sound at some point?”, “A lot of noise, I guess, sounded like a lot of friction coming through. Those I struggled a bit with in terms of actually feeling something or being immersed into that.”*
- **P1:** *“Yeah, at one stage one of the blocks sounded like a weird... made a weird, out-of-this-world kind of sound.”*
P2: *“Like a... it’s not the right sound.”*
P1: *“It felt like I didn't feel... as much as with the blocks that actually had a realistic sound.”*

In each of these cases, the participant did not know which possible tactile experience to associate with the audio and/or visuals or the audio and/or visuals contradicted what they had expected from the object (*“it’s not the right sound”*) and could thus not create the expectation of a texture to feel in their hands. It was only in the cases when their expectations of real blocks were met that they could experience a touch-sensation, as illustrated more explicitly in the following comments:

- *“I think room 1 especially really recalled more memory of what I would expect a block to feel like, especially because of the texture of the different blocks sounded very close to what I would imagine it to be.”*
- *“...if I'm inside and I close my eyes, which I do, and then I feel something, it's hard to describe what it is. But if you actually have visual cues you actually tell me ‘you’re touching this, you’re touching that’, it's much easier to make a link to something in the real world and convince yourself that object is something else.”*
- *“It literally felt like ‘this [sound] fits with the texture’ and it felt like there was the most interaction with [that block].”*

- “For me room 1 was the strongest, because I could see what the block was. So, I already had an expectation, like ‘oh, this looks like sandpaper, feels like sandpaper’ or ‘looks like a carpet, feels like a carpet’.”

For this reason, an illusory tactile sensation is regarded as implying a successful cross-modal transfer: for participants to experience an illusory tactile sensation, they first need to cross-modally map the audio and/or visual information created by the block to a real-world texture they know. Morrot, Brochet and Dubourdieu’s (2001) notion of the cognitive component present in discerning sounds also seemed to influence perception of tactile sensations, such as the case where one participant above noted that they “*can’t really touch electricity*” (Morrot, Brochet & Dubourdieu 2001). This is notably different than the perception of several other participants who noted that some blocks evoke the feeling of static electricity. The difference in thinking about this possible texture, i.e. static electricity vs. (presumably) current electricity, seemed to allow some participants to feel an illusory tactile sensation while preventing the aforementioned participant from experiencing this.

A possible explanation as to why participants needed the expectation of a real-world texture in order to experience an illusory touch-sensation relates to the bilateral nature of touch as a sensation, i.e. the fact that the experience of touch always implies an exchange of energy and information between an individual and a physical environment (Salisbury & Srinivasan 1997). Using one’s physical body, for example, one’s hands, is one of the most basic ways to explore the physical world and the properties of physical objects, such as weight and texture (Salisbury & Srinivasan 1997; Robles-De-La-Torre 2006). This experience of touch as an experience that implies direct interaction/contact with a physical object/environment with real-world properties is different from visual and audio sensations in this regard: one can experience abstract representations in other modalities, such as synthesised sounds which do not occur in nature (Moffat 2016), such as the aforementioned “*out-of-this-world*” sounds, but since touch is inherently bilateral, the same does not apply (Salisbury & Srinivasan 1997; Robles-De-La-Torre 2006). This lack of a believable texture which participants could expect while touching a virtual object would thus prevent them from being able to suspend disbelief and accept their experience as a believable touch-sensation, which is discussed further in section 5.2.4.3.4.

The bilateral nature of touch is expected to also require a high level of believability for the virtual hands, as participants would need to be able to not only perceive them as believable objects with physical properties and behaviours, but would also need to maintain a sense of hand-ownership as discussed in section 5.2.4.2.2. Since touch-sensations require direct interaction/contact with a physical object/environment, participants would only be able to

conceive of believable touch-sensations if they could believe that the virtual hands were theirs and that they were “touching” the virtual objects without mediation. This was supported by the data, as all participants who noted illusory touch sensations noted a sense of hand-ownership, whether it was explicitly or implicitly as discussed in section 5.2.4.2.2, with the exception of one participant who did not refer to the virtual hands at all during any of the data collection.

The next topic that participants commonly cited as influencing the realism and believability of the VE is the internal consistency of the virtual world.

5.2.4.3.2 Internal consistency

While the expectations of certain behaviours and attributes from the real world informed participants’ perceived realism of the VE to an extent, participants also noted the consistency of the VE in terms of its behaviour and attributes as shaping their perception of the world. This was discussed explicitly during the expert focus group while discussing the importance of realism:

- **P1:** *“I also just want to add on that, the whole thing of, if you expect [the VE] to behave in a certain way, if your first interaction was not how you expected it, but it consistently behaves in that way, the player can also become accustomed to that and then it would eventually become how the player expects it to be.”*
- **P2:** *“So then, consistency is important. So, it still comes back to, sort of, being predictable, so if you learn what the pattern is then you can predict it.”*

And then later when discussing how participants were still able to perceive the virtual environment as being real despite the obvious unrealistic elements, such as the hovering blocks and teleporting:

- **P1:** *“I think it goes back to the whole consistency thing, because if it was consistent that each block that you press down would come back up then you accept it as the norm in that context. Same with the [teleportation mechanism].”*
- **P3:** *“Yeah, I’d say also willing suspension of disbelief, like, you’re in it, the first thing you see is the environment and it doesn’t change, it’s consistent the whole way through, so you accept that as what it is and so it’s still real, it doesn’t matter if it’s not real, like real-life real [sic].”*

This notion of being able to process the environment as being real due to the environment presenting itself as an internally consistent reality is similar to the notion of consistency of sensory outputs by Lombard and Ditton (1997), which states that the consistency of

information regarding the VE in all modalities needs to be consistent in order to describe the same objective world/reality, which also helps participants suspend their disbelief (Lombard & Ditton 1997) as described by participant 3 above. It is also similar to the notion put forth by Biocca et al. (2002) that, similar to our perception of the physical world, we require consistent, shared information between senses to construct an internally consistent model of the virtual world (Biocca et al. 2002). This can be seen in the response of participant 1 above in their statement that consistency in the behaviour of the VE allows one to “*become accustomed to [the consistent behaviour of the VE]*” and “*accept it as the norm in that context*”, which in turn creates an expectation of how the world should behave and continue behaving. Participants could thus create a mental model of the virtual world (Regenbrecht, Schubert & Friedmann 1998; Biocca et al. 2002) consisting of virtual objects, which also needed consistent behaviours, as illustrated in the following comments, both describing the creation of a mental model in terms of “*a(n) image/picture in your head/brain*”:

- “*For me [the sensation of touch in] room 1 was the strongest, because I could see what the block was. So, I already had an expectation, like 'oh, this looks like sandpaper, feels like sandpaper' or 'looks like a carpet, feels like a carpet'. So that helps again, like I said the sound creates a picture in your head and then I associate the feeling... if I see it first it's the same thing, just stronger.*”
- “*So, suppose the first room you put a picture of sandpaper and then when you rub it: sandpaper. Automatically your brain will say 'ok, this feels like sandpaper'. Next room you put picture of cardboard [points to piece of cardboard in the room], feels like [rubs on piece of cardboard], then all your senses can be stimulated at once. Then your brain can form an image and actually feel whatever you're feeling at that moment.*”

Apart from participants' explicit discussion of consistency as an influence on the realism and believability of the world, consistent behaviours were also implicitly mentioned as helping participants create a mental model of how the VE functions:

- “*[because of the colours] you almost feel relaxed immediately and then I played around with them, in every room obviously had the same kind of function when I would push it down and stuff.*”
- **Participant:** “*I feel I mostly had the same experience in every room, if that makes sense, I feel like hearing lead me to want to touch the block each time.*”
Researcher: “*What do you mean with that?*”
Participant: “*I don't know, it's sort of a confirmation: if you touch the block there is a sound and it also confirms that you're touching the object.*”

- *“So, each time you would scratch, I picked up one sound, it sounded like you're scratching a carpet. Especially when you scratch the top layer of the box. And the same thing happens when you pull it down, when you push it up, you get a feedback. So that's when you get to realise 'ok, there's interaction between myself and the object'.”*

Each of the participants above noted the consistent behaviour of the blocks as objects that can be moved up and down and that produce a sound when touched. In the case of the second participant, the consistent sound-producing behaviour of the block also acted as a “confirmation” that helped establish their mental model of the blocks in the VE (Regenbrecht, Schubert & Friedmann 1998). Conversely, when behaviours or sensory outputs were inconsistent, this had the opposite effect of highlighting the artificiality of the environment (Lombard & Ditton 1997):

- *“Up until [block 3] the sounds are very natural, what you would expect, and then the last block is very... it's a combination of the sci-fi [sic] with the natural sounds.”*
- *“...I've heard this sound before, can't really place it. I don't know, it's kind of just weird and it doesn't really match up, like what I'm seeing is this kind of flat surface and then the sound it emits is just... weird to me.”*
- *“Sometimes when I touched the same surface with both hands the sound only came from the first hand's location. This felt odd. Also, when I removed my hands, the sound kept on playing for 1 second. This then felt that I was in a simulated environment.”*

It should be noted, in reference to the third participant's comments regarding the perceived origin of the sound, that participants were instructed to only use one hand at a time in order to prevent that issue from occurring. All of these participants had constructed a mental model of the VE to create an expectation of the behaviour of the blocks based on reality and previous blocks in the VE. When that expectation was not met, in other words, when the behaviour did not align with the perceived internal consistency of the environment, the possible realism or believability of the reality was negatively affected (Lombard & Ditton 1997).

The same occurred when the virtual hand behaved unexpectedly due to Leap Motion tracking issues, as discussed during both focus groups:

Non-expert focus group

- **Participant:** *“Sometimes when you would switch your hand, sometimes it would feel like your hand is disappearing in the block.”*
Researcher: *“What was the effect of this on your overall experience?”*
Participant: *“That again just stated that this is not real. That was the main effect.”*

Expert focus group

- **Participant:** *“I think on that as well [sic] is the whole consistency thing where my brain wouldn't expect the [irregular inversion of the hand] to be consistent and there wasn't a specific type of interaction that caused the tracking to go off. So, I wouldn't be able to associate it with a specific action for that to happen and it comes back to consistency.”*
Researcher: *“So the fact that the tracking was sometimes a bit [unreliable] and the fact that it was unexpected [had a negative effect on your experience or kept you from feeling that you were part of that world]?”*
Participant: *“Yes.”*
Researcher: *“So you have no idea of predicting what has a negative effect on your tracking?”*
Participant: *“Yes.”*

In this case, the participants have already constructed a mental model for the behaviour of their virtual hands. Since the behaviour of the virtual hands correspond very closely with the behaviour of their real hands, due to the Leap Motion's tracking accuracy (Butt et al. 2017), participants were quick to notice this inconsistency, as it also negatively affected their sense of personal presence, as discussed in section 5.2.4.2.2.

Although discussed much less frequently, binaural audio was also cited by four participants as having an effect on their mental model of an internally consistent virtual world, as exemplified by the following comments:

- *“Which block I rub is which side the sounds are for me [sic]. I don't know if all of [the rooms] are like this, but I notice it more in room 3.”*
- *“If I rub on the left, I only hear it on the left...”, “I can sort of determine where on the left [the block] is.”*
- *“If I rub this block the sound is focused there on my left, so if I move the left block I hear the sound there. Same with this block. So, it helps to create a three-dimensional space in my brain, in my mind's eye.”*
- *“[For some of the blocks], when I rubbed it, I don't know if it was intentional, but the sound came from the left ear while it felt as if it should have been the right ear...It made it feel unnatural.”*

The first two participants simply describe the binaural audio as a behaviour of the block. The third participant was the only one who described it as shaping their model of the 3D environment. For the fourth participant, observation data suggest that their left hand was still

being tracked by the Leap Motion while they were using their right hand to rub the block, which caused the sound to be played from the left hand's location in 3D space. However, it provides further evidence that they constructed a mental model of the behaviour of the sound with regards to rubbing the block which included the 3D position of the sound source and when presented with stimuli that was inconsistent with this mental model, it reduced the believability of the virtual world.

Before discussing participants' willingness to suspend disbelief and its effect on participants' illusory tactile sensations, the relationship between expectation and consistency, as discussed by participants, is briefly explored.

5.2.4.3.3 Expectation and consistency

While discussing both expectation and consistency, the perception of each seemed to refer to the other in many cases. For the sake of illustration, two remarks from participants are included here, which illustrate cases where expectation informed perceived internal consistency and vice versa.

- **Expectation informs consistency:** *“When I, for example, rub with my fingertips [the volume is] very soft and that's actually how it is in the world when I normally rub [objects].”*

In this case, the consistent behaviour of the sound-producing block correlated with the participant's notion of rubbing objects in the real world, which informed their mental model of the behaviour of the blocks and their hands.

- **Consistency informs expectation:** *“...[touching the block is] sort of a confirmation: if you touch the block there is a sound and it also confirms that you're touching the object.”*

Here the “confirmation” that occurs when touching the block implies an expectation to be confirmed, which is informed by the previous behaviour of the blocks. Thus, the existing mental model of the sound-producing blocks created an expectation when interacting with more blocks. However, consistency can also exist in the absence of a real-world expectation, as illustrated by the following comments regarding the obviously unrealistic nature of certain behaviours, such as the hovering blocks and teleporting:

- *“I think it goes back to the whole consistency thing, because if it was consistent that each block that you press down would come back up then you accept it as the norm in that context. Same with the [teleportation mechanism].”*

- *“...if your first interaction was not how you expected it, but it consistently behaves in that way, the player can also become accustomed to that and then it would eventually become how the player expects it to be.”*

Here, the participant was able to construct an internally consistent behavioural mental model for the blocks, despite their lack of verisimilitude compared to the participant’s natural environment, since, as another participant stated, *“...consistency is important. So, it still comes back to, sort of, being predictable, so if you learn what the pattern is then you can predict it”*.

The next section discusses participants’ willingness to suspend disbelief and the factors which allow them to do this, including expectation and internal consistency.

5.2.4.3.4 Suspension of disbelief

As discussed briefly in section 5.2.3.1, many of the participants who experienced illusory tactile sensations noted being conscious of the fact that the environment around them is not real and that their hands are not actually touching anything. Despite this, they continued to experience the aforementioned as being *“there”* or *“real”*, as illustrated by the following remarks during interviews:

- *“It’s very weird to know subconsciously that there’s no block actually there, but when I’m immersed into [sic] the virtual environment it almost feels like there are actual blocks in front of me.”*
- *“It was strange to think that [the environment] is there, but it isn’t really there.”*
- *“In your brain you know it isn’t there, but kind of if I’m there it feels... understand? It really feels real.”*
- *“It was strange to interact with an environment that isn’t really there, but you do have an effect on it.”*

As this was a topic that was discussed by many participants, it was followed-up on during both focus groups. It should be noted that since the discussion surrounding this topic has already been included under section 5.2.4.3, only parts of participants’ remarks are reiterated:

Non-expert focus group

- **P1:** *“...I feel like we’re in such a technological era, like even when I game I get so used to it and it feels so real that, although it’s literally impossible for a block to hover, it feels real to me, because, why not? I’m used to it.”*

- **P2:** “...you almost go into the VR, the system, with an open mind and I didn't mind if I saw blocks hovering because I was like 'cool, I'm going into this kind of space where things like this are possible'. So, it didn't seem unrealistic, even though it is unrealistic.”
- **P3:** “Because I feel like I'm going into a game environment.”
- **P4:** “I also think because the whole experience was new, you don't really focus on things that are not normal, you're taking everything in at once.”
- [later in the same focus group]
- **P2:** “...your mind is really weird when no senses are actually working, but all your senses are actually working [sic]. That makes no sense, but in that kind of environment I think, because it's a virtual environment your imagination kind of goes with it and that's what happened with me...”

Participant 1, 2 and 3 all attributed their ability to suspend disbelief and accept unrealistic or impossible events as real to the experience of entering a different type of environment, which is described by participant 3 as a “*game-environment*”. Participant 2 also described their suspension of disbelief as having an “*open mind*”, similar to the notion of a cooperative mind-set (Sheridan 2000), as well as that “*your imagination kind of goes with it*”. Participant 4 notes that they were new to the experience of using a VR system, which, in their case, contributed to their suspension of disbelief. However, only one other participant directly connected the novelty of the experience to their suspension of disbelief: “[*Room 1*] I think definitely had the biggest effect, because that was, besides the initial [introductory] room, because that was the one where everything was still new and my head was still wrapping around everything [sic]”.

Thus, while the blocks in room 1 were most effective in inducing an illusory tactile sensation, there are not sufficient data to directly connect novelty to suspension of disbelief for the current study. There is also evidence to suggest that some participants experienced the opposite, i.e. that they had to adjust to the experience before being able to suspend their disbelief, which is discussed below. However, responses from the expert focus group regarding suspension of disbelief are first discussed. Similar to the discussion above, only parts of participants' remarks are listed:

Expert focus group

- **P1:** “...you only experience a sense of touch if only you allow the game consume you...”, “If you are distracted by other things or thinking about other things, you won't feel anything, because your mind will tell you, 'look, this isn't reality'. For me if you're consumed by the game and you love what you are doing and it's something interesting to you, only then can you feel a sense of touch.”

- [later in the same focus group]
- **P2:** “...it does depend on the context; if the context is something that's requiring me to suspend my disbelief then realism is not that important. Whereas if it's something like, I don't know, you're in a room and you're touching stuff then that would be better if I could actually feel that I was touching those things, as opposed to not.”
- [later in the same focus group]
- **P2:** “Yeah, I'd say also willing suspension of disbelief, like, you're in it, the first thing you see is the environment and it doesn't change, it's consistent the whole way through, so you accept that as what it is and so it's still real, it doesn't matter if it's not real, like real-life real [sic].”

In this case, participant 1 directly linked their ability to perceive an illusory sensation to their willingness to “allow the game to consume you”, which highlights the subjective nature of suspension of disbelief (Lombard & Ditton 1997) and is attributed largely to involvement, similar to the notion of avoiding factors that would enhance disbelief (Sheridan 2000). Participant 2 above, the only participant who specifically used the term “suspension of disbelief” throughout any of the data collection, emphasised the context in which the experience took place, i.e. the media form and content (Lombard & Ditton 1997), as having an effect on how much they would have to suspend their disbelief to “accept that as what it is”, along with the consistency of the environment.

This notion of a threshold of suspension of disbelief or the ease with which participants were able to suspend their disbelief was also noted by other participants during their interviews:

- “[I only experienced tingling sensation when] any form of, with the fingers, with the hand... [sic] with the palm or back of my hand, for specific things, for when it made sense, like with the carpet and then the sound of the carpet, I think everything added together and then maybe potentially warped my brain into thinking 'this could potentially be something' and that initiating a reaction of some sort.”
- “...so, let's say I felt like it was real life, the blocks, although, like you said, they were hovering and it wasn't actually able to be real, it felt very real until that point. Or I felt like that block made that [abstract sound] and it just made me realise 'ok, this is a game-type [environment]'...”
- **Researcher:** “Does [rubbing the second and third block in room 6] create the same [touch] sensation as the other rooms?”
Participant: “No, [the sounds in room 6] are somewhat jarring. The other stuff, most of the other rooms, are more... believable? And this one, the sounds that you're... I don't know, it just feels unnatural.”

All three of these participants noted that they could only experience illusory sensations or experienced them the strongest when it was “easy enough” for them to suspend disbelief in that context (Lombard & Ditton 1997). This type of comparative description of their experiences between different rooms, i.e. the fact that certain aspects of the objects/environments allowed them to or prevented them from suspending disbelief enough to experience those objects/environments as real, points toward a “threshold” in the degree or amount of suspension of disbelief required from participants. The first participant required the combination of visual and audio stimuli that “*made sense*” in order to feel, in their case, a tingling sensation in their hands, whereas the other two participants described the believability falling below a required threshold, which emphasised the artificiality of the environment and prevented it from being believable.

Other participants also noted having to exercise different degrees of suspension of disbelief during different parts of the experience:

- “*I think with [room 2] it was just that soft sound, so because it sounded like there wasn't too much... maybe because my brain didn't have to make too much of a jump in terms of actually feeling something; it's like fur, you don't really feel lots, it's very soft in your hand and the sound would match that. And with the wood, similar, it was a very smooth wood, not a very harsh sound, not a very... not hard for my brain to jump like 'oh, is my hand running through air or is it actually running along a smooth piece of wood?', with the occasional little bump or defect.*”
- “*...if you actually have visual cues you actually tell me 'you're touching this, you're touching that', it's much easier to make a link to something in the real world and convince yourself that object is something else.*”

Both of these participants note a variability in the “*jump*” or “*link*” one’s mind has to make in order to suspend disbelief and experience the virtual world as a possibly real one. The first participant experienced the closest touch-sensation when the texture they thought was being simulated did not contain a lot of textural information, as evident in their descriptions of the textures: “*it's like fur, you don't really feel lots*” and “*the occasional little bump or defect*”, which required less suspension of disbelief to be perceived as believable. Similarly, the second participant emphasised the “*link*” to something in the real world as reducing the required amount of suspension of disbelief in order to “*convince yourself that object is something else*”.

As already discussed, two participants noted the novelty of the experience as helping them suspend disbelief. However, one participant also noted the opposite, i.e. they had to adjust to the experience in order to suspend to disbelief to experience an illusory tactile sensation:

- *“Room 1 was like, you have to get comfortable, so I was still very aware [sic] that it’s not reality. So, I was like: ‘oh, I feel it... not really, but I hear the sound’.”*, *“It was something to get used to, the first room was still very much like: ‘oh, no, I don’t know’. And then as I went further into the experience and forgot about... outside, it became more realistic. So, it was this gradual going into the thing [the experience] and as I went in I was like ‘ok, yes’, it’s very nice to be able to feel the textures in VR.”*

This participant’s remarks clearly indicate an adjustment to the virtual world, which is somewhat indicative of the ability to focus more on certain experiences of a VE and less on factors that might diminish the perceived believability of the VE (Sheridan 2000).

Another participant also noted an experience which seems to contradict both experiences of novelty and adjustment:

- **Researcher:** *“You say it freaked you out that you felt it, but you know you didn’t?”*
Participant: *“Exactly.”*
Researcher: *“Would you say it’s a bit of a cognitive dissonance?”*
Participant: *“Yes, but it could also be that I sort of became attuned to it, but it was also, you know, it wasn’t from the start. It builds [sic].”*
Researcher: *“So you’re saying it builds and you get attuned...”*
Participant: *“No, so I was attuned from the start, like, I am busy with VR, I’m just sitting here, but as it went on, as I felt [the blocks], I realised I don’t really feel them.”*
Researcher: *“So it became more disconnected?”*
Participant: *“Yes.”*

This participant’s remarks are more complex: they describe becoming “*attuned*” to the mismatch between their virtual experience and real-world experience (of sitting in a room), which made them uneasy as they realised that their sensations are illusory. These remarks, along with the fact that they cited room 1 as being the most effective in creating illusory touch and displayed visible behaviour of recoiling after “touching” the virtual blocks in room 1, suggest that they could suspend disbelief from the start of the experience, but became more consciously aware of the artificiality of it as they carried on. However, this did not keep them from “*feeling*” the virtual blocks, but rather caused unease as they realised their touch-experiences were artificially induced.

Another aspect related to adjustment to the VE, which has already been discussed, is the description of getting more comfortable with the VE:

- *“I think at first when you... you first have to accustomise [sic] yourself to the touch and to being able to do things, like the instructions were great, because then you know you were able to do this and you can do that. But as soon as you get comfortable with it, it was really cool how I could do anything, like I said I started pushing the blocks down and playing with it like this and it was cool because it was so realistic.”*
- **Researcher:** *“In which room would you say what you experienced came closest to actual touch?”*
Participant: *“I personally think that when you get to room 7, the later rooms for me, because then you understand your environment better and the sound when you touch it, I have to say, it feels as if it can really be like that...”*
Researcher: *“So the later rooms, because you understand how it works?”*
Participant: *“Exactly. And you feel more comfortable in your environment.”*

Both of these participants’ remarks are indicative of an increase in willingness to suspend disbelief as they became more comfortable with their surroundings; however, since discussions regarding getting comfortable in VR have already taken place in sections 5.2.4.2.1 and 0, they are not repeated here. All four of the examples regarding adjusting to the VE illustrate how suspension of disbelief can vary across time as individuals get used to the experience or get comfortable with their surroundings (Lombard & Ditton 1997).

The next section discusses how all three of these factors influence the illusory perception of touch as described by participants.

5.2.4.3.5 Expectation, consistency, and suspension of disbelief

As mentioned in the previous two sections, both expectation and internal consistency contributed to participants’ willing suspension of disbelief. Participants needed the expectation of a real-world texture in order to suspend their disbelief of the virtual object in order to experience an illusory tactile sensation while “touching” that object. This is possibly due to the bilateral nature of touch, as discussed in section 5.2.4.3.1, since interacting with a texture a participant could not recognise as part of the real world would require too much of a “jump” or “link”, i.e. it would be above their individual threshold of suspending disbelief. Participants also constructed mental models of an internally consistent virtual world using knowledge from the real world and the virtual world. When this “*image/picture in their minds*” was confirmed they could continue suspending disbelief, as exemplified by the

following remark: “...if you touch the block there is a sound and it also confirms that you’re touching the object”.

Conversely, if participants experienced inconsistencies in the behaviour of the virtual world or if their expectations regarding textures they could map to real-world sensations were not met, as in the case of many of the abstract sounds as well as inconsistent hand-behaviour caused by Leap Motion tracking issues, they could no longer ignore the clear indications that the world/environment they were experiencing was artificial (Lombard & Ditton 1997), and thus could not conceive of a believable sensation as a reaction to their interactions.

This was also discussed in section 5.2.4.3.1 and is illustrated by the following exchange:

- **Researcher:** “Which types of sounds made [the experience of touching] more real?”
- **Participant:** “[The blocks] that sound rough, as if you really have a block that has sandpaper kind of, if I can put it like that, on it. Where with the futuristic sounds [sic] you can feel it’s not really real...”

The same applied for the small number of participants who noted the binaural audio: the ability to localise sound in 3D space, similar to the real world, helped establish the believability of the virtual world and when this behaviour, as well as any “unnatural” sound behaviour, contradicted the perceived internal consistency of the virtual world, it prevented participants from being able to enact enough suspension of disbelief to keep on experiencing the virtual world as possibly real, for example: “Sometimes when I touched the same surface with both hands the sound only came from the first hand’s location. This felt odd. Also, when I removed my hands, the sound kept on playing for one second. This then felt that I was in a simulated environment [sic]”. Thus, the complex interplay between expectation, internal consistency, and willing suspension of disbelief helped create a believable mental model of a virtual world which participants could inhabit, which created the possibility of experiencing illusory tactile sensations while interacting with virtual objects.

As stated at the beginning of this section, realism was established as the single most pervasive cause of illusory tactile sensations, as noted by participants. Participants noted that the resemblance of the VE to the real world, i.e. verisimilitude, directly influenced their perception of illusory touch, mentioning the visual appearance of the environment and/or objects as well as their “realistic” behaviour, such as producing sound when being rubbed. However, upon further inspection, the topic of “realism” described by participants often referred to believability rather than verisimilitude, specifically when referring to the perceived realism of blatantly unrealistic objects/behaviours. Because of the lack of distinction between these two concepts in the way participants described their “realistic” experiences, these two

concepts were not described separately; instead, three factors were identified which were often cited as influencing both concepts: expectation, internal consistency, and willing suspension of disbelief.

The concept of realism as verisimilitude can easily be explained by way of explaining participant expectations: participants entered the VE with certain expectations regarding the appearance and behaviour of the objects and environments based on their experiences from the real world and when these expectations were met, they could experience the VE as “realistic”. However, the concept of expectation in this context was not limited to verisimilitude, as participants could also adapt their expectations to behaviours that were not similar to real-world behaviours, in which case they would have to learn how these behaviours work in context, in which case these potentially unrealistic behaviours became “transparent”. Participants could thus base their expectations on real-world behaviours as well as adjust them based on the perceived internal consistency of the VE.

Another finding related to expectation was the requirement for participants to attribute their illusory touch-sensations to real-world touch-stimuli. This was confirmed both in the affirmative, all participants except one who experienced illusory tactile sensations compared them to real-world textures, and in the negative, the lack of effective illusory touch-sensations was often explained by participants’ inability to match the perceived texture created by the VE to real-world textures. For this reason, illusory tactile sensations implied effective cross-modal information transfer, as a perception of a real-world texture was considered a requirement for an illusory tactile sensation. A possible explanation for this requirement is the bilateral nature of touch, which requires a touch-sensation to be directly in relation to a real-world texture to be believable, as this is part of the nature of touch-sensations in the real world. If a real-world texture was not present or plausible, participants could not cross the threshold of suspension of disbelief to experience the texture as real or possibly real. The same was expected to hold true for participants’ sense of hand-ownership, as participants would need to temporarily believe that the virtual hands were their own hands, which would allow them to experience illusory touch sensations through their virtual hands.

The environment presenting itself as an internally consistent reality, which was referred to in this section as the internal consistency of the VE, was also instrumental in participants’ process of constructing a mental model of the world/reality. Participants could construct a mental model of the blocks as possibly real objects with believable behaviours and attributes, including tactile texture, if the appearance and behaviour of the blocks were consistent and experienced the objects and environments as artificial when this consistency was not maintained. Although expectation and consistency were found to be correlative, they were

not interchangeable, since either could inform the other and vice versa. Furthermore, consistency could also exist without expectation, since participants were able to learn how the environment and objects behaved, regardless of their similarity to the real world. Thus, internal consistency contributed to an illusory sense of touch by helping participants construct their mental models of the VE, which could, in turn, inform “*how the player expects it to be*” and thus what they “should” be experiencing. In the absence of behaviours that corresponded to participants’ expectations from reality, such as the hovering blocks or teleportation mechanism, the ability to construct an internally consistent mental model by “learning the pattern” allowed participants to still experience the virtual world as a believable entity that could induce believable physical sensations.

As discussed in section 5.2.3.1, participants were able to experience objects/environments as real despite knowing that they're not, as they were able to suspend their disbelief for the duration of the usability test. Some participants attributed this to the novelty of the experience, however, the relationship between novelty and suspension of disbelief was unclear as there was relatively little evidence to inform this relationship and the evidence itself was inconclusive, as it pointed towards both novelty and adjustment as determinants of suspension of disbelief. The subjective nature of suspending disbelief was confirmed, as participants described a “threshold” of believability that needed to be maintained through the appearance and behaviour of the objects and environment. Suspension of disbelief was thus described as a variable experience which relied on different aspects and properties of the objects and environment for different individuals. Thus, in the absence of a VE that was able to perfectly replicate the real world, participants needed to suspend their disbelief during their experience in order to perceive the VE as a believable world/entity that was able to induce real sensations, such as touch, in order to experience illusory tactile sensations.

5.3 Summary

This section started with an evaluation of the results of the pilot usability test to inform changes to the final tests. Some problems with the existing testing and data gathering procedures were identified and the refined procedures were discussed. For the sake of the credibility of the final results, the prototype’s levels of comfort and usability were then evaluated using the quantitative and qualitative results of the final usability tests. The prototype was found to be comfortable to use insofar as that it did not induce well-known undesirable side effects that commonly result from using VR systems, such as motion sickness. These quantitative and qualitative results were also used to evaluate usability and presence, which indicated that participants were able to use the prototype with ease due to the interaction mechanisms being perceived as natural and intuitive. Participants also described

feeling physically transported to the VE created by the prototype for the duration of the experience.

Before discussing the main focus of the current study, four adjacent and unintended illusory phenomena were discussed. During the usability tests, a small number of participants described illusory kinaesthetic feedback, perceived room temperature changes, perceived room size changes, and perceived changes in sound produced as a result of rubbing the virtual blocks with different parts of their hands, the most-observed of these being illusory kinaesthetic feedback. Although these illusory effects were described infrequently, largely because of the fact that they were not part of the focus of the current study and thus were not targeted during data collection, they were still discussed in this chapter for two reasons: firstly to indicate them as promising topics of further investigation regarding illusory tactile phenomena and secondly because their underlying causes as described by the participants that experienced them alluded to some of the main themes that form part of the focus of the current study. Although the qualitative results drawn on when discussing these effects were scant, they pointed towards the importance of participants' ability to perceive objects and environments as believable enough to possess physical properties and behaviours, which would allow these properties and behaviours to be perceived even if they were not presented via any sensory modalities. Some of these effects were in line with existing findings obtained from real-world studies, such as a tendency to associate low pitch with weight and a change in perceived room size depending on room colour. However, the fact that these findings held true in a virtual space points toward the effectiveness of the VR system in creating the illusion of an unmediated experience while participants experienced the VE created by the prototype.

The remainder of the chapter was dedicated to an in-depth investigation into the focus of the current study, starting with an evaluation of the effectiveness of the prototype in achieving its goal of inducing illusory tactile sensations in participants while interacting with virtual sound-producing blocks in VR. The prototype was found to be effective in this goal, as 18 out of 23 participants described experiencing some sort of illusory tactile sensation. Furthermore, 16 out of these 18 participants described these sensations without being prompted about their tactile experiences, which suggests that the prototype could effectively induce illusory tactile sensations. The nature of touch-sensations, as described by participants, were grouped into two categories: experiences of illusory textures and tingling sensations resulting from perceived touch with a virtual object. The most pervasive of these categories was an experience of touching an illusory texture, which was explained by the manner in which participants mapped audio and visual feedback to tactile textures and how that allowed them to experience the sensation of interacting with virtual objects as a real touch-sensation.

Participants could effectively map textural information using audio and visual feedback, although the exact nature of the mapping between combinations of real-world recordings and abstract sounds and the corresponding tactile textures was found to be highly subjective and dependent on how participants used the prototype, thus an attempt to determine mappings between these combinations and real-world texture descriptions was not made. Because of this, there was also no emphasis made on the “correctness” of participants’ mappings between audio and tactile stimuli. However, participants’ descriptions of these mappings highlighted a notable finding regarding illusory tactile experiences, which is that they were always described with reference to real-world textures, with the exception of one participant. In a later section, this was hypothesised to be due to the bilateral nature of touch-sensations themselves, as these are always experienced with reference to real-world objects and thus the sensation of touch cannot be decoupled from interaction with a real object as in the case of “abstract” visual or audio stimuli which can exist without a real-world equivalent. Three factors of abstract audio were also identified which were frequently described as detracting from the believability of virtual blocks as sound-producing objects: the inability of these sounds to be associated with real-world objects or events, the perceived musical quality of some of these sounds, and the high pitch of some of these sounds.

The next section focused on investigating the underlying causes of illusory tactile experiences, which were often attributed to the perceived realism and/or believability of the VE as well as various descriptions of presence, the latter of which was discussed first. Although involvement is already known to have a correlative effect on presence, the occurrence of involvement alone was noted by some participants as directly influencing their perceptions of illusory touch. Two known factors were found to affect this involvement: the integrated use of information across more than one sensory modality and the subjective cognitive strategy which some participants employed while interacting with the prototype. Descriptions of presence were found to align with existing dimensions used to describe presence and thus these dimensions were used to categorise these descriptions of presence. Similar to how believable virtual objects allowed participants to attribute physical properties and attributes to them, believable hand behaviours, despite the lack of realistic graphical representation, allowed participants to “inhabit” their virtual hands. This was largely attributed to the close correspondence between participants’ hand movements and the resulting virtual behaviour, which allowed participants to experience the virtual hands as “their hands” and allowed them to use their virtual hands to feel illusory texture. It was hypothesised that this sense of hand-ownership is a requirement for experiencing illusory tactile feedback, as the bilateral nature of touch-sensations requires our touch-receptors to be in direct contact with whatever is being felt, which presupposes that whatever is being used to touch an object, be it real or virtual,

must be perceived as part of an individual's body to function as a sensory organ. Since the only virtual body representation offered by the prototype was that of the virtual hands, these were the only mechanism through which participants would be able to perceive a sense of tactile stimuli.

The behaviour of the objects and environment which reacted to participants' actions as well as the range of interactions afforded by the prototype were frequently noted by participants as making the VE seem more "real" or "realistic" to them. As a matter of fact, the realism of the appearance and behaviour of the objects or environment was the single most-cited cause of illusory tactile sensation described by participants. However, behaviours that participants included in their descriptions of realism were not limited to behaviours that directly corresponded to those found, or even possible, in reality; rather, a number of impossible behaviours and attributes of the prototype were still being described by participants as "realistic". Thus, the notion of realism as a precise resemblance to reality, referred to as verisimilitude in the current chapter, was insufficient for the current study and a more encompassing notion, believability, was used alongside realism to categorise instances where participants described their experiences as real or possibly real. Under this broader category, three factors were identified which influenced participants' perception of the VE as a possibly real environment and which allowed them to inhabit this environment.

The first of these factors related to the manner in which participants built expectations with regards to the appearance and behaviour of the prototype and the extent to which these expectations were met during their interactions with the prototype. As most of the prototype was meant to simulate a real environment in terms of the appearance of the environment and objects as well as the core interaction used throughout the prototype, participants relied on their tacit knowledge to establish their expectations of how the prototype should look, sound, and behave. However, expectation in this context was also found to be malleable, as participants could adapt their expectations in instances where object behaviours did not correspond with real-world behaviours and which participants could thus not derive the nature of these behaviours from real-world equivalents. In these cases, participants were still able to conceive of successfully supported actions by learning the internally consistent, albeit physically impossible, behaviours presented by objects in the VE and by doing this, could conceive of them as believable in the context of the VE.

The second of these factors related to the aforementioned internal consistency with which the VE presented itself and maintained its own presentation. This related to the manner in which participants were able to construct an effective mental model of the VE, which required that the appearance and behaviour of the VE remained consistent throughout the experience of

using the prototype. Participants could thus internalise their learned set of successfully supported actions as part of their mental model of the behaviour of the world/reality presented by the VE, which allowed them to conceive of believable touch-sensations as they interacted with virtual objects. These believable touch-sensations informed their expectations of what they “should” be experiencing while interacting with the virtual objects, which contributed to their sense of illusory touch.

Both these factors also contributed to the third factor, which was participants’ ability to suspend their disbelief in the possible realism of the prototype for the duration of the experience. As participants constructed mental models of the world/reality and as these were continually confirmed by the internally consistent VE, participants were able to keep their suspension of disbelief above a threshold and experience the VE as possibly real or believable. This threshold was found to be highly subjective, as participants attributed the perceived realism, or conversely the perceived artificiality, of the VE to different aspects of the VE’s behaviour and appearance. As suspension of disbelief is inversely correlational to believability, suspension of disbelief also contributed to the perception of illusory tactile sensations by allowing participants to conceive of believable touch-sensations while interacting with virtual objects.

This next chapter discusses the conclusions of the current study as obtained through various forms of data collection and the analysis and discussion of this data.

6. Chapter 6 - Conclusion

This chapter concludes the dissertation by summarising the results of the study and discussing these results in order to answer the research questions. The chapter is then concluded by listing the contributions made by the study followed by a discussion regarding recommendations for future work.

6.1 *Summary of the study*

This study focused on the creation of illusory tactile feedback in VR by means of inducing it through intersensory illusions with audio feedback. This was carried out by first reviewing the literature to investigate a number of related topics, such as the creation and use of both tactile and audio feedback in VR, the relationship between audio and tactile feedback, the nature and causes of intersensory illusions, and the role of immersion and presence in the experience of VR systems. This investigation in turn informed the design and development of a software prototype which aimed to make use of specialised interaction mechanisms and induce illusory tactile feedback in the total absence of this type of feedback being produced in reality. The design of this prototype was directly informed by the following guidelines from the literature:

- **Immersion and presence:** by identifying which aspects of the design of a VE was crucial in a user's sense of being "transported" to the VE and experiencing themselves as "being there", some important issues were addressed, such as the required degree of realism in the representation of this VE, technical requirements for the VR technology, and design decisions which aid users' perception in the illusion of presence. These aspects would also aid in the discussion of participants' experiences while using the prototype.
- **Intersensory illusions:** in order to successfully design an interface that is able to induce perceived stimuli in an unstimulated sensory modality, other intersensory illusions and their causes were investigated, including the directionality of which sense triumphs during this interchange of conflicting sensory feedback.
- **Mapping between audio and tactile:** the inherent relationship between the audio and tactile modalities was investigated to identify ways to cross-modally map information between them. This informed a set of parameters which could be used to design an interface able to intuitively map texture-information from the audio to the tactile modality.

The research design to make use of the prototype to achieve its goal took the form of a usability test, which involved 23 participants selected using purposive sampling. Data regarding participants' experiences during the test were gathered using direct observations, questionnaires, interviews, and focus groups. As the bulk of these data were qualitative, they were then analysed using the constant comparative method and the results presented and discussed in chapter 5.

6.2 Findings of the study

The findings of the study are discussed by referring to each of the sub-questions of the study. The main research question of the current study is then answered.

6.2.1 Sub-questions

Each of the current study's research sub-questions are answered here in turn in order to allow for the main research question to be adequately addressed.

6.2.1.1 Sub-question 1: Which characteristics of both audio and haptic feedback can be utilized to design an effective intersensory illusion between them?

This question was answered by investigating the literature on cross-modal mapping and information transfer between the audio and tactile modalities as well as by the empirical data of the current study.

A number of parameters of stimuli common to both modalities were identified and narrowed down to four which could be created and controlled by means of interacting with the prototype. It was believed that utilising these parameters would aid in the creation of audio stimuli that is conducive to the perception of illusory tactile feedback. These four parameters, as discussed in section 4.2.2.4.2, were as follows:

- **Timbral qualities:** by selecting different sounds and waveforms for the audio feedback. In the prototype, this was done by selecting and combining different variants of recorded audio and synthesised audio for different blocks. The types of audio to be used were divided into three categories, one of which utilised recorded audio that corresponded with two recognisable tactile textures and the other two applied different strategies to utilise synthesised audio notes.
- **Pitch:** the pitch of the synthesised audio was controlled by the participant's hand velocity and the vertical displacement of the block. A conscious decision was made not to vary the starting pitch of the synthesised audio between blocks in order to reduce the number of variables that differ between blocks.

- **Amplitude:** the amplitude/volume of the sound being played was controlled by the participant's hand velocity for all types of audio. Again, the degree to which hand velocity affected sound amplitude was purposefully not varied between blocks in order to reduce the number of variables that differ between blocks.
- **Spatial location:** the blocks were located at various locations around the participant in 3D space and, since the prototype made use of binaural audio, the audio playback was implemented so as to always be localised to a participant's hand rubbing the block.

The details of which audio combinations were perceived as which tactile textures were not investigated in depth, as the study did not focus on detailed information mapping between modalities and since the use of the prototype in different ways was expected to influence the resulting audio feedback in different ways. However, some common themes regarding the use of these parameters were found. Firstly, although purely synthesised audio feedback, as described in section 4.2.2.4.2 and 4.2.2.4.3 as the “abstract” strategies, was relatively ineffective in inducing illusory haptic feedback when used on its own, the use of this audio in combination with recorded audio as well as other synthesised audio was found to be much more effective in this goal. Furthermore, as a result of the combined use of various strategies, participants noted feeling a number of textures that no audio was explicitly recorded for, such as blackboard, sand, and static electricity. The combined use of recorded and synthesised audio thus presents the potential to create the perception of a variety of tactile textures in the absence of audio recordings that correspond to each of these textures individually.

Secondly, one of the audio strategies, which utilised synthesised audio and played back short musical notes randomly from the chromatic scale across four octaves starting from C two octaves below middle C, was often perceived as being “unnatural”, “synthetic”, etc. and thus counterproductive in the goal of the prototype. Participants noted three main reasons explaining why these sounds tended to be less effective at inducing illusory tactile feedback, the first of which was the synthetic quality of the sounds and their inability to be associated directly with real-world objects. Another reason was that, despite an attempt at making them seem less inherently musical by using the chromatic scale instead of, for example, the major or minor scale, some participants still experienced them as musical, which also prevented participants from being able to associate them with real-world objects. The third reason given was simply the high pitch that the blocks were able to produce, the negative effect of which, as suggested by interview and observation data, could be reduced by limiting this pitch to two octaves above middle C instead of the four octaves used for the prototype.

The use of binaural audio to give audio feedback a position in 3D space was noticed relatively infrequently by participants but was noted to have contributed to the believability of the 3D virtual world, or in one case, a malfunction in the perceived spatial location was noted to have the exact opposite effect. Thus, the use of these four parameters aided in the creation of an interface which used audio interactively to induce a variety of illusory tactile sensations.

6.2.1.2 Sub-question 2: Which underlying causes of intersensory illusions can be utilised to induce illusory tactile sensations?

This question was answered by the review of the literature and the empirical data of the current study.

In order to investigate the manner in which sensory stimulation in one modality is able to alter/induce perception in another modality, the relationship and interplay between senses were discussed in section 2.4.3, with emphasis on the process of integrating feedback from different modalities, which is known as intermodal integration. While it was traditionally believed that the overall perception of information across all modalities is merely a summation of each sense's contribution in isolation, more recent evidence suggests that the senses influence each other in complex ways in order to construct a stable mental model of one's reality. When conflicting feedback is presented across different modalities, the intermodal integration process has been known to alter feedback in one modality in order to maintain the stability of an individual's mental model of reality. These phenomena are known as intersensory illusions and have been observed across a range of modalities, such as the size-weight illusion, double flash illusion, and McGurk illusion.

For the purposes of the current study, a specific type of intersensory illusion known as cross-modal transfer was targeted, since the aim was to induce illusory tactile feedback in the absence of any real-world tactile stimulation. The review of the literature revealed a number of factors which are known to cause these illusions, such as the expectation that is carried over from the real world regarding the resulting sensory stimulation from interacting with virtual objects. Furthermore, the repetition of corresponding stimuli in two or more modalities and shared properties between modalities were both expected to contribute to this illusion and the integrated use of more than one modality to influence a third was expected to have an effect that is greater than the sum of what either modalities contribute to on their own.

Although the combined effect of two or more sensory modalities was not tested, empirical data revealed that the virtual room making use of integrated audio and visual feedback was the most effective at inducing illusory tactile feedback. Expectation carried over from the real

world was also found to be one of the main contributors to the believability of the VE, which also contributed to the induction of illusory tactile feedback. This expectation also manifested in the repetition of corresponding stimuli, as participants could construct a mental model of the behaviour of the VE, which they could then confirm with continued use of the prototype. Thus, the prototype's ability to present internally consistent feedback and behaviours allowed participants to construct a coherent mental model of the world/reality created by the prototype. Finally, shared properties between modalities were used to inform the design of the prototype and were found to contribute to its goal, as discussed above in section 6.2.1.1.

6.2.1.3 Sub-question 3: What is the role of immersion and presence in the creation of illusory tactile feedback?

This question was answered by the review of the literature and the empirical data.

Often used synonymously and incorrectly, immersion and presence are integral concepts for any discussion regarding VR and any experiences with VR systems as it differentiates VR from other media technologies and experiences. Immersion is often used to describe the ability of VR systems to isolate users from the outside world and only deliver feedback regarding the VE; in other words, the ability to “immerse” users in the VE. This definition, however, is inadequate and only describes one aspect which can be categorised as part of the immersive aspects of a system. For the purposes of the current study, immersion in VR is defined as the total of a set of objectively quantifiable aspects of the sensory output that the system delivers using displays, such as audio, visual and haptic. This definition frames immersion as a continuum of objectively measurable qualities, such as visual/audio fidelity, end-to-end latency, etc. which exist separately from the user's perception and experience while using the system.

Presence, on the other hand, refers specifically to the user's perception and experience as a result of the immersive aspects of the system. The term presence is often used to describe the experience of “being there”, which is also an inadequate summary, as the underlying processes which create this illusory sense of being transported reveal a number of insights regarding our reaction to VR technology. For the purposes of the current study, presence is defined as an involuntary state of consciousness whereby a user of VR uses immersive stimuli to construct a mental representation of a VE, including a virtual body which “becomes” their body in VR. The user enacts a degree of suspension of disbelief to invoke the illusion that they are having an unmediated experience of the surrounding environment, although they are at all times consciously aware that they are not physically located in this environment. The result of this experience is that they feel physically “present” inside the VE.

A number of factors have been found to contribute to the sense of presence, such as Heeter and Allbritton's (2015) four dimensions of presence:

- **personal presence:** comes from the user's perception of their body in VR as well as being able to control it
- **social presence:** comes from other social beings in the VE who react to the user's actions (which was not applicable to the current study)
- **environmental presence:** comes from the reaction of the virtual environments and objects to the user's actions
- **embodied presence:** comes from the user paying attention to and reacting to emotions and feelings so as to connect to their sense of self. This concept stems from the notion of "introspection", which refers to being aware of physical sensation, such as temperature or pain, in the real or virtual world.

The intuitiveness of the link between actions and outcomes in the VE also helps users feel like they are located in the VE, which could be the result of the naturalness/transparency of this link, i.e. a lawful response given by the system, or because the user has learned the link and is able to apply it in context. Since presence manifests itself as a state of consciousness, the level of presence is also affected by the user's physical and mental attributes.

A related concept which is sometimes equated with either immersion or presence is the amount of attentional resources that a user allocates to the experience of using a VR system, which is called involvement. Although the current study does not regard involvement as mutually inclusive with either immersion or presence, involvement is often regarded as having a correlative effect on presence, as allocating more attentional resources is expected to encourage suspension of disbelief and possibly a state of flow. This correlative relationship was also supported by empirical data from the current study. Empirical data also indicated that involvement itself contributed to an illusory sense of touch and was affected by the integrated use of more than one sensory modality as well as participants' cognitive strategy while using the prototype.

Three of the four dimensions of presence were cited by many participants as a contributor to an illusory sense of touch, with social presence not being included as it was not applicable to the current study. Personal presence in the form of body-ownership, specifically hand-ownership, was seen as a requirement for experiencing illusory tactile feedback. The reason for this is that our sense of touch in the real world is inherently bilateral and always requires direct contact with objects via our touch receptors. Thus, for a touch-illusion to be believable would require that participants are able to conceptualise of virtual hand representations as

their own hands and that this sense of hand-ownership is believable enough to allow for a sense of touch using those hands. Participants experienced environmental presence through being able to enact changes on the environment by means of interacting with the virtual blocks. This further added to the perception of the VE as a believable reality that is able to produce various types of sensory feedback. Participants also experienced embodied presence by being cognisant of their own sensory experiences, such as noting a sense of illusory touch, which was often accompanied by an awareness of the impossibility of this experience. A smaller number of participants also noted their internal state, such as being relaxed or anxious, which some participants explained with their use of a cognitive strategy throughout the usability test.

Thus, various forms or dimensions of presence related directly to the perception of illusory touch sensations, which relied on the immersive aspects of the VR system and participants' willingness to allocate attentional resources to the experience.

6.2.1.4 Sub-question 4: How can the effectiveness of the intersensory illusion be tested?

This question was answered by the review of the literature and empirical data.

This question related to the research design that was employed to gather data regarding the design and testing of an interface aimed at inducing illusory tactile feedback. Since illusions relate to an experiential and therefore highly subjective aspect of human perception, a qualitative design was chosen in order to study participants' reactions to a software prototype designed to induce illusory tactile feedback. The research method consisted of a usability test, using a pilot test to finalise the testing procedure. Participants were introduced to the technology and given instructions on how to use the prototype, during which observation data were collected in the form of video- and screen-recordings. After interacting with the prototype, participants were given a presence-questionnaire, the ITC-Sense of Presence Inventory (ITC-SOPI), to gather quantitative data regarding their levels of presence and comfort as well as optional qualitative data regarding their overall experience. After filling out the questionnaire, participants were interviewed, which constituted the main data gathering method, in order to discuss the main topic of the research and gather rich, descriptive data regarding many aspects of their experience. Out of 23 participants that took part in the usability test, 10 participants later took part in focus groups, which followed up on emerging themes from previous data gathering and explored these emerging topics in more depth.

Different data gathering methods revealed different insights for measuring the effectiveness of intersensory illusions. The first method, observation, revealed behavioural data for a small number of participants which indicated, very clearly in one instance, an intuitive reaction

towards “feeling” a texture, which took the form of participants recoiling their hands as their interactions produced visual and aural feedback. However, with the exception of one instance where a participant also verbally signalled displeasure at interacting with some of the virtual blocks, this type of behaviour on its own would not necessarily signal illusory tactile feedback as other factors could also cause this participant to draw back their hands after touching the virtual blocks, such as adjusting to the novelty of the experience, exploring the possible range of interactions, etc. For this reason, observation data were always considered in conjunction with other forms of data gathering, such as interview or focus group data.

Since the goal of the ITC-SOPI for the current study was to collect data regarding participants’ levels of presence and comfort, it contributed relatively little data to the main focus of the study. However, three questions from this questionnaire related directly to the study’s focus and thus were used as part of the confirmation of the prototype’s effectiveness in achieving its goal. Since the questionnaire was administered before the interview took place, participants were not aware of the study’s focus on tactile feedback, and thus detailed correlations between the scores for the three aforementioned questionnaire questions and their subjectively-described tactile experiences were not determined, but low combined scores for these questions were found to correspond with interview data describing a weak or non-existent sense of touch. Furthermore, high scores for presence and engagement and low scores for “negative effects” given on the questionnaire indicated high levels of desirable aspects of immersion, such as inclusivity and natural interaction, and low levels of undesirable aspects, such as latency. The relationship between immersion, presence, and the focus of the current study is discussed above in section 6.2.1.3.

As mentioned, the main data gathering method used for the current study was a qualitative interview with each participant after using the prototype. It was only at this point of the testing and data gathering procedure that the main focus of the study was explored directly by means of specifically asking participants key questions about their experiences of tactile sensations while using the prototype. However, caution was also taken at this point to avoid leading questions and unintentionally prime participants to frame their experiences in terms of their tactile sensations. This was done by moving these key questions to the end of the interview and exploring participants’ experiences in broad terms before asking directly about their tactile experiences. The questions that explored their overall experiences were also worded in broad terms, in other words, without referring to any specific sensory modality. These measures were taken because of the perceptual and thus highly subjective nature of intersensory illusions with the goal of allowing participants to express their experiences and highlight what they perceived as notable parts of those experiences themselves. This approach

proved to be effective, as most participants who noted illusory tactile feedback did so before reaching the key questions, in other words, without being specifically asked about their tactile experiences, which lends credibility to their responses.

Finally, two focus group sessions were held at a later date which were used to follow up on emerging themes and make use of the group dynamics of focus groups to gain insight into complex topics that influenced participants' sense of touch during the usability tests. Both of these sessions contributed valuable insights into the underlying causes of participants' illusory tactile experiences. The use of segmentation to divide participants into different groups based on their previous VR- and/or gaming-experience also proved useful, as participants were able to communicate clearly with one another and make use of concepts and terminology which corresponded to their own and their fellow participants' levels of experience with these technologies.

Thus, the combined use of different data gathering techniques with each being used according to its own strengths allowed for a large amount of rich, descriptive data to be collected. Participants' sensory experiences were described and explored in-depth in order to gain insight into the underlying causes which allowed some participants to experience illusory tactile feedback while using the prototype and thus measure the effectiveness of the prototype in achieving its goal.

6.2.2 Main research question

Having answered each of the research sub-questions in turn, the main research question can now be addressed: *How can the illusion of tactile feedback be created using binaural audio in virtual reality to induce intersensory illusions?*

Sub-questions 1, 2, and 3 (sections 6.2.1.1, 6.2.1.2, and 6.2.1.3) each discussed the use of the literature in the design of a software prototype that uses a variety of insights from the literature, specifically the relationship between the audio and tactile modality, underlying causes of intersensory illusions, and aspects of immersion, to inform the design of a VR prototype that is able to induce illusory tactile feedback. Sub-question 4 (section 6.2.1.4) discussed the design of a study in order to test the effectiveness of this prototype, which made use of qualitative data and was carefully designed around the subjective nature of illusions.

In order to answer the main research question, the effectiveness of the prototype was discussed in section 5.2.3.1, followed by a discussion of the factors which were noted to play a role in the perception of a combination of audio and visual feedback as an illusory touch-sensation. Some of these results were also preliminarily discussed in sub-questions 1, 2, and 3.

Sub-question 1 discussed the shared parameters between the audio and tactile modality and how these parameters affected an illusory sense of touch. Sub-question 2 discussed some known underlying causes of intersensory illusions and confirmed some of these using empirical data. Sub-question 3 discussed the role presence in its various forms played in allowing participants to experience themselves as sharing a virtual space with virtual objects and allowing them to conceive of believable touch sensations from interacting with these objects.

The factor which was most essential in the creation of illusory tactile feedback, however, was the realism/believability of the VE. This was found to rely on expectation participants carried over from the real world and/or constructed while using the prototype as they constructed a consistent mental model of the world/reality presented by the VE. This requirement manifested itself in the requirement that participants are able to cross-modally map audio to real-world textures, which is also expected to be a result of the bilateral nature of touch, which only allows one to conceive of a virtual texture that corresponds to a real-world texture. For participants to maintain their mental model, the VE also needed to be internally consistent and meet participants' expectations as they continued to interact with virtual objects. In order to experience an inexact replica of reality as believable, participants also needed to suspend their disbelief and accept impossible behaviours as realistic in the context of the VE. The required degree of suspension of disbelief was found to vary among participants and rely on different aspects of the VE for different participants, including the ability of the VE to meet their expectations and the internal consistency of the VE.

Thus, the prototype was able to present participants with a combination of audio and visual stimuli that they were able to use to construct the illusion of an accompanying sense of touch. This relied on the realism/believability of the world/reality presented by the VE, which participants could use to construct a mental model of a world/reality that was able to produce tactile sensations as a result of interacting with virtual objects.

6.3 Contributions of this study

As mentioned in section 2.4, discussions surrounding the use of the audio and tactile modalities tend to be neglected in favour of discussions surrounding the visual modality. The main contribution of the current study is therefore the design of a software prototype able to induce illusory tactile sensations using a combination of visual and audio feedback, with the design of the prototype focusing on the use of audio. The prototype was found to be successful in achieving its goal and the illusory feedback was found to be robust enough to

persist after participants became aware of the impossibility and therefore illusory nature of their sensory experiences.

The success and failure of different audio implementation strategies to achieve this goal also revealed insights regarding the illusory perception of touch stemming from the bilateral nature of touch, which showed that illusory touch is always the result of interactions and feedback that can be conceived of as delivering believable touch sensations. A believable mechanism for experiencing touch is therefore required, such as virtual hands which a user of VR experiences and temporarily conceives of as their own hands, as well as believable virtual textures, delivered through audio feedback, which participants can map to real-world textures, since touch experiences always relate directly to real-world textures.

Underlying causes of illusory tactile feedback were divided into two main categories and both of these were elaborated on with subcategories of causes. This included detailing the relationship between immersion and presence and illusory tactile feedback as well as a discussion regarding realism/believability, including how this was established and maintained as well its contribution to illusory tactile feedback.

The combined use of recorded and synthesised audio revealed insights into the design of audio feedback that is meant to be perceived as believable. Synthesised audio was able to induce intersensory tactile feedback, but needed to be associable with real-world textures, not be perceived as musical, and be limited in pitch to be perceived as believable enough to induce these sensations. The combined use of recorded and synthesised audio could also create perceived textures that were not recorded, which thus presents the possibility of creating a variety of perceived tactile textures without needing recordings for each.

The review of the literature produced a consolidated, although non-exhaustive, list of low-level factors of immersion which are organised according to high-level categories, which is provided in section 2.3.1.2. The discussion surrounding immersion and presence also produced consolidated definitions of both terms, favouring the approach taken by Slater, Usoh and Steed (1995) to separate the two terms and define the relationship between them.

6.4 Recommendations for further research

The current study revealed a number of topics that would benefit from further investigation, which are discussed here.

6.4.1 Unintended illusory effects

In addition to illusory tactile feedback, the prototype also produced four other illusory effects, which are discussed in section 5.2.2. These effects were:

- illusory kinaesthetic feedback from pushing blocks up and down
- differences in perceived room temperature depending on room colour
- differences in perceived room size depending on room colour
- changes in sounds produced depending on hand position.

Although illusory kinaesthetic feedback has been observed in other studies, such as two studies done by Biocca, Kim and Choi (2001) and Biocca et al. (2002), the aforementioned studies used a visual analog of a haptic force in the form of a spring connecting objects to their origin. Since the current study did not make use of such an analog, it was found that the perceived believability and physicality of the blocks were enough to create the same illusory effect for some participants.

However, since none of these illusory effects were planned for in the design of the current study, they were not investigated in-depth and require further study to understand their causes.

6.4.2 Proximity effect

As discussed in sections 2.5.5.3 and 4.2.2.5, the design of the prototype included the use of what is known as the proximity effect because of its potential to enhance the cross-modal capability of audio feedback by giving audio recordings a perceived “intimacy”. However, as the current study did not make use of an experimental approach to test effectiveness of different audio strategies, the effects of the proximity effect were not tested in any detail. More research is needed to determine the effects and usefulness of this effect in the context of sound design for VR.

6.4.3 Realism and believability

The discussion regarding the causes of illusory tactile feedback hinged on the concepts of realism and believability, as these were most often cited as the cause of this feedback. However, as the delineation between these two concepts is not clearly defined, the current

study did not attempt to discuss the influence of both concepts separately. These concepts were therefore discussed together in section 5.2.4.3.

More research should be conducted to define the nature of these concepts as separate but related determinants of a user's experience while using VR. This should include investigation into the causes of perceived believability as a result of or despite the objective realism or unrealism provided by a VE.

6.4.4 Individualised factors

A number of physiological and psychological factors that are known to influence presence are listed in section 2.3.2.2, which were not included in the scope of the current study. As these factors have the potential to affect an individual's experience inside a VE, they also have the potential to influence their perception of intersensory illusions. More research should therefore be conducted to determine individualised factors that could add to or detract from the perception of illusory feedback, which should also include strategies to design for or compensate for these factors.

6.5 Summary

This chapter concludes the dissertation. The current study designed and developed an implementation of a VE that is able to successfully and robustly induce illusory tactile feedback.

The findings indicate that it is possible to exploit a number of underlying mechanisms and shared properties between modalities to create the illusion of sensory stimuli in the total absence of such stimuli in the real world.

This chapter has summarised the study and discussed the outcome of the study by referring to the research question and sub-questions. The contributions made by the study were outlined and recommendations for further research were made.

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Appendices

6.6 Appendix A – Questionnaire

The ITC-Sense of presence inventory was created by Lessiter et al. as discussed in (Lessiter et al. 2000) and (Lessiter et al. 2001). The ITC-Sense of Presence Inventory was used with permission of the authors after agreeing to the terms of use as stipulated below:

1. *that [the researcher] wish to use the questionnaire for research purposes,*
2. *that [the researcher] will not distribute it to anyone outside your laboratories/institutions, without prior written (email) consent from [the authors], and in no instance for financial gain,*
3. *that [the researcher] will respect the copyright of i2 media research ltd on the questionnaire,*
4. *that [the researcher] will provide [the authors] with copies of completed questionnaires (or completed SPSS database - request by e-mail) with a brief description on each questionnaire of the media experience and media system each respondent experienced prior to completing the questionnaire (NB [the researcher does] not need to describe the goals of [the] research or send any of [the researcher's] other data – [the authors] require large data sets to validate the questionnaire, and a general description of the media experience suffices in this regard), and*
5. *that in any reports or publications describing data from [the researcher's] use of the questionnaire [the researcher] cite the current best reference for the questionnaire: Lessiter, J., Freeman, J., Keogh, E., & Davidoff, J.D. (2001). A Cross-Media Presence Questionnaire: The ITC Sense of Presence Inventory. Presence: Teleoperators and Virtual Environments, 10(3), pp 282-297.*

Upon agreeing to these terms, written authorisation to use the questionnaire as well as the questionnaire itself was granted to the researcher.

6.7 Appendix B – Interview questions

(Note: the ITC-SOPI questionnaire was used to measure the amount of presence experienced by the user during the test in order to triangulate this data with their account of their experience during the test, as given in the interview. In order to prevent bias in their answers, participants were only told that the purpose of the test was to investigate the perception of sensory phenomena in virtual reality, with no mention of intersensory illusions, tactile feedback or binaural audio. Prior to data collection, it was explained that the questionnaire and interview focus on collecting different types of data, but both are focused on their experiences during the test. The word “experiment” was used instead of “test”, so as to frame their participation as an exploration rather than a performance in order to reduce possible anxiety.)

The experiment involved a number of virtual rooms, each with a number of virtual blocks that the user could interact with, using their hands. The implementation of the binaural audio solutions was encapsulated in the interaction with these blocks. Each room was a different colour on the inside, to allow participants to recall specific rooms more easily.

The interview was semi-structured, with the questions listed below. Every interview was recorded using a voice-recorder. Participants were given refreshments before the start of the interview. Information regarding their previous gaming- and VR-experience (listed below as x and y) was obtained from their answers on the ITC-SOPI questionnaire, as the interview took place directly after the questionnaire was filled in.

The interview started with a primer, explaining the details of the interview:

Just to reiterate, there are no right or wrong answers during this interview. The only right answers are your honest opinions and experiences during and after using the VR system.

Question 1

You indicated on the questionnaire (*referring to the ITC-SOPI*) that you have x^* amount of experience playing video games. Can you elaborate on your answer?

** x referred to their answer on the ITC-SOPI questionnaire*

Question 2

You also indicated that you have y^* amount of knowledge on virtual reality and virtual reality technologies. Can you elaborate on that answer?

** y referred to their answer on the ITC-SOPI questionnaire*

Question 3

How would you describe your experience inside the virtual environment during the experiment, especially while rubbing the blocks?

[Point out that if they cannot remember, they can go back to refresh their memory]

Question 4

How would you describe your experience in terms of any notable sensory experiences in the first room?

Question 5

How would you describe your experience in terms of any notable sensory experiences in the second room?

(This question was repeated for each virtual room)

Question 6

In which room would you say what you experienced came closest to actual touch?

Question 7

Can you elaborate on why that room's touch experience felt more real than the others?

Question 8

How would you summarise your overall experience in terms of your sense of touch during the experiment?

Question 9

Did you experience anything else that we haven't discussed that you think is noteworthy and would like to add?

If you remember anything else, please let me know.

(At this point, the researcher's contact information was given to the participant)

6.8 Appendix C – Informed consent form for interviews

1. Project information

1.1 Title of research project: Using binaural audio to induce intersensory illusions to supplement the lack of tactile feedback in virtual reality.

1.2 Researcher details:

- Mr. De Villiers Bosman
- Information Science Department
- Contact Number: 084 988 8294
- Email Address: isak.bosman@up.ac.za
koos.debeer@up.ac.za
theo.bothma@up.ac.za

1.3 Research study description: This research project will investigate the perception of sensory phenomena in virtual reality. Participants will be required to use virtual reality technologies to interact with virtual objects and provide feedback on their experiences. It must be noted that participants may become fatigued or nauseated as a result of prolonged use of virtual reality equipment, although precautions have been taken to avoid this.

2. Informed consent

2.1 I, _____

hereby voluntarily grant my permission for participation in the project as explained to me by Mr. De Villiers Bosman.

2.2 The nature, objective, possible safety and health implications have been explained to me and I understand them.

2.3 I understand my right to choose whether to participate in the project and that the information furnished will be handled confidentially. I also understand that I may leave the study at any time for any reason. I am aware that the results of the investigation may be used for the purposes of publication.

2.4 I hereby agree to being recorded in the form of voice recording during the interview and focus group and video recording during the test. I am also aware that no personal information or any information that can be used to identify me will be recorded.

2.5 Upon signature of this form, the participant will be provided with a copy.

Signed: _____ Date: _____

Witness: _____ Date: _____

Researcher: _____ Date: _____

6.9 Appendix D – Focus group questions

(Note: all participants from the test were asked to join the focus groups at a later date. The participants were divided into two groups: those with substantial computer gaming and/or VR experience, listed below as Group 1, and those without, i.e. Group 2. This grouping was determined and managed using the answers and contact information given on the ITC-SOPI questionnaire. Similar to during the interview, the word “experiment” was used instead of “test” when referring to the usability test, so as to frame their participation as an exploration rather than a performance in order to reduce possible anxiety.)

The interview made use of a pre-established structure consisting of a set of questions, as listed below. Most of the session was voice-recorded starting from question 2, so as to maintain confidentiality. Participants were given refreshments before and after the focus group session as their reward.

Both focus groups started with a primer, explaining the purpose and details of the focus group:

Same as the interviews, there are no right or wrong answers during this discussion. The purpose is to get everyone’s opinions and experiences in their own words.

Question 1

For the introductory question, the two groups were asked slightly different questions. The aim of this was to establish rapport between participants that play games by drawing attention to their collective gaming-experience.

Group 1: Can everyone please introduce themselves by giving their names, what they are studying or have studied in the past, and their favourite video game at the moment?

Group 2: Can everyone please introduce themselves by giving their names and what they are studying or have studied in the past?

(Voice recording started at this point)

Question 2

Explain your feelings toward virtual reality. Are you interested, disinterested, excited, apathetic, etc.?

Question 3

It is widely accepted that a sense of touch is important for making sense of the real world, but how do you think virtual reality would benefit from being able to provide a sense of touch, i.e. a tactile experience?

Question 4

For the next couple of questions, I want to discuss a few topics that kept coming up in the interviews, the first being realism.

(A number of sub-topics of realism were discussed, including the importance of realism, the effect of unrealistic interactions, the effect of acting on the environment on perceived realism, and the malleability of realism).

Question 5

The next topic is that of the role of the environment: did anyone experience different effects or feelings in the different rooms because of the room colours? Such as temperature?

Question 6

Another topic that came up during the interviews was a sense of pressure when pushing the blocks. Did anyone experience something like this?

Question 7

Some of you also noted feeling a sort of a sense of touch during the experiment, can anyone elaborate on this? Can anyone elaborate on the nature of this "sense-of-touch" experience?

Question 8

Those who did feel a sense of touch, can you elaborate on where it was and what made that room or those block different?

Question 9

During the interview, when discussing blocks and their differences, most of you used textural descriptive words to describe blocks, even those who didn't "feel" anything. Can anyone elaborate on the reason for this?

Question 10

Was there anything specific in the virtual environment that diminished your experience or kept you from feeling that you were part of the virtual world?

(The following were brought up: "digital" sounds, inconsistent behaviour of hands, specific rooms, and colours and lighting.)

Question 11

(During the discussions, the researcher kept track of the main points and briefly summarise them. At this point, this summary was read out to all participants)

Does *(the summary)* adequately summarise everyone's experiences?

Question 12

Have I overlooked anything noteworthy or interesting that you still want to discuss?

(Participants were thanked for their time and given the remainder of the refreshments)

6.10 Appendix E – Informed consent form for focus groups

1. Project information

1.1 Title of research project: Using binaural audio to induce intersensory illusions to supplement the lack of tactile feedback in virtual reality.

1.2 Researcher details:

- Mr. De Villiers Bosman
- Information Science Department
- Contact Number: 084 988 8294
- Email Address: isak.bosman@up.ac.za
koos.debeer@up.ac.za
theo.bothma@up.ac.za

1.3 Research study description: This research project will investigate the perception of sensory phenomena in virtual reality. Participants will be required to use virtual reality technologies to interact with virtual objects and provide feedback on their experiences. It must be noted that participants may become fatigued or nauseated as a result of prolonged use of virtual reality equipment, although precautions have been taken to avoid this.

2. Informed consent

2.1 I, _____

hereby voluntarily grant my permission for participation in the project as explained to me by Mr. De Villiers Bosman.

2.2 The nature, objective, possible safety and health implications have been explained to me and I understand them.

2.3 I understand my right to choose whether to participate in the project and that the information furnished will be handled confidentially. I also understand that I may leave the study at any time for any reason. I am aware that the results of the investigation may be used for the purposes of publication.

2.4 I hereby agree to being recorded in the form of voice recording during the interview and focus group and video recording during the test. I am also aware that no personal information or any information that can be used to identify me will be recorded.

2.5 Upon signature of this form, the participant will be provided with a copy.

Signed: _____ Date: _____

Witness: _____ Date: _____

Researcher: _____ Date: _____

6.11 Appendix F – Ethics approval for data collection



Faculty of Engineering, Built Environment and Information Technology

Fakulteit Ingenieurswese, Bou-omgewing en
Inligtingtegnologie / Lefapha la Boetšenere,
Tikologo ya Kago le Theknolotši ya Tshedimošo

Reference number: EBIT/129/2017

6 December 2017

Mr ID Bosman
Department of Information Science
University of Pretoria
Pretoria
0028

Dear Mr Bosman

FACULTY COMMITTEE FOR RESEARCH ETHICS AND INTEGRITY

Your recent application to the EBIT Research Ethics Committee refers.

Approval is granted for the application with reference number that appears above.

1. This means that the research project entitled "Using binaural audio to induce intersensory illusions to supplement of the lack of tactile feedback in virtual reality" has been approved as submitted. It is important to note what approval implies. This is expanded on in the points that follow.
2. This approval does not imply that the researcher, student or lecturer is relieved of any accountability in terms of the Code of Ethics for Scholarly Activities of the University of Pretoria, or the Policy and Procedures for Responsible Research of the University of Pretoria. These documents are available on the website of the EBIT Research Ethics Committee.
3. If action is taken beyond the approved application, approval is withdrawn automatically.
4. According to the regulations, any relevant problem arising from the study or research methodology as well as any amendments or changes, must be brought to the attention of the EBIT Research Ethics Office.
5. The Committee must be notified on completion of the project.

The Committee wishes you every success with the research project.

Prof JJ Hanekom
Chair: Faculty Committee for Research Ethics and Integrity
FACULTY OF ENGINEERING, BUILT ENVIRONMENT AND INFORMATION TECHNOLOGY