Examining the Effects of Embodiment on Performance and Learning of Drilling Actions using Pseudo-Haptics and Standard Computer Equipment

By

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An oral defense of this thesis took place on August 14, 2023, in front of the following examining committee:

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The above committee determined that the thesis is acceptable in form and content and that a satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate during an oral examination. A signed copy of the Certificate of Approval is available from the School of Graduate and Postdoctoral Studies.

ABSTRACT

Psychomotor skills training within virtual learning environments are limited due to the need for expensive haptic devices to simulate haptic cues. While pseudo-haptics presents an accessible and cost-effective alternative to haptic devices, no empirical data support the notion of coupling it with embodiment which is crucial for psychomotor skill development. This thesis explored the effect of embodiment, represented by a virtual hand, coupled with pseudo-haptics on the performance and learning of a virtual drilling task. Using a mixed methods approach, 40 participants performed a virtual drilling task using a developed specifically for this purpose. The results show that when coupled with pseudo-haptics, embodiment significantly improves the speed of acquisition of the task indicating the need for a virtual hand in a virtual psychomotor-based simulation when coupled with pseudo-haptics. Although greater work is required, these results may lead to a convenient cost-effective virtual psychomotor-based simulation using standard computer equipment.

Keywords: Embodiment; Psychomotor skill Development; Pseudo-Haptics; Multimodal Interaction; Virtual Learning Environment

AUTHOR'S DECLARATION

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Sandy Abdo

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Table of Contents

LIST OF TABLES

CHAPTER 4

CHAPTER 5

LIST OF EQUATIONS

CHAPTER 3

LIST OF FIGURES

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

LIST OF ABBREVIATIONS AND SYMBOLS

VLEs	Virtual Learning Environments
2D	2-dimensional
3D	3-dimensional
VR	Virtual Reality
1PP	First-Person Perspective
3PP	Third-Person Perspective
MLSs	Learning Management Systems
SoE	Sense of Embodiment
fMRI	Functional magnetic resonance imaging
RH	Rubber Hand
HMD	Head-Mounted Display
AR	Augmented Reality
MR	Mixed Reality
C/D	control/display
GEQ	Game Engagement Questionnaire
PC	Personal Computer
RMSE	Root Mean Square Error
E	Embodiment
NE	Non-Embodiment

Chapter 1. Introduction

1.1 Overview

This chapter will start by outlining problems and gaps in the current literature and the rationale and motivation behind this thesis work. The research question and the objectives of this work will follow. The chapter ends with the aim and a listing of the thesis hypotheses.

1.2 Problem Statement

For decades, simulation has been used to educate learners, including those in the healthcare field, in a safe and effective manner [1, 2]. Simulation-based training encompasses more traditional physical simulations such as mannequins, standardized patients and task trainers, and digital simulation in the form of virtual learning environments (VLEs) [1, 2]. However, despite the growing popularity of VLEs, including virtual simulations and serious games, VLEs typically focus on cognitive and affective skill development, paying less attention to psychomotor skill development [3]. All of these three domains of learning (i.e., cognitive, affective, and psychomotor) are essential for effective professional development and training [4]: i) the cognitive domain involves the understanding and strategies to recall complex information; ii) the affective domain, involves learners' emotions toward learning and develops strategies to progress from low to high processing order; and iii) the psychomotor domain involves physicality such as physical presence and involvement in activities, and the establishment of motor skills needed for performance [4].

This lack of emphasis on the psychomotor domain is due to two reasons [5, 6]: i) the technical difficulties with simulating the realistic haptic experiences (sense of touch) needed for psychomotor skills development [3, 5], and ii) the lack of coupling of psychomotor skills development with embodiment [6].

1) There are technical difficulties with simulating the realistic haptic experiences (sense of touch) needed for psychomotor skills development without costly haptic devices.

Most haptic devices are both expensive, ranging between 2,800 USD and 34,400 USD in 2021, and require a large storage space due to their bulkiness, making it challenging to acquire and store them [7, 8]. To resolve the consumer-level shortage of these devices, the field of pseudo-haptics has emerged. Pseudo-haptics uses visual and/or auditory cues coupled with standard computer equipment (e.g., a computer mouse), to mislead the brain and to provide the user the impression of the sense of touch [5, 9]. Originally driven by the COVID-19 pandemic and the resulting shift to remote learning, prior work has focused on pseudo-haptics to provide a cost-effective method of medical-based psychomotor skills development. Ning et al. (2023) conducted a study that examined whether a virtual drilling task (a commonly used skill in medicine such as orthopedic surgery, intraosseous infusion, and dentistry) [3] can be appropriately simulated using pseudo-haptics, and more specifically, combinations of visuals and sound was able to induced kinesthetic stimuli (the feeling of muscle, tendon and joints movement and the sensation related to them [9]) obtained with movement of a basic 2D mouse in the absence of haptic devices. Although preliminary, the results of this experiment indicate that kinesthetic cues conjoined to a standard computer mouse can be used to provide a suitable perceptual drilling experience without a haptic device [5]. However, Ning et al. (2023) disregarded a fundamental component for psychomotor skill acquisition, which is embodiment, the sense of being inside and controlling a body inside a virtual space. This gap leads to the second reason: the lack of coupling psychomotor skills development with the sense of embodiment.

2) The lack of coupling of psychomotor skills development with embodiment.

An important factor in effective psychomotor-based VLEs is the sense of embodiment, the experience of being inside and consciously controlling a body [10]. Embodiment is fundamental to psychomotor skill development as one cannot acquire any new skill without being bodily present to generate, control, and exploit movement [11]. Despite the importance of embodiment in psychomotor development, often it is not considered in psychomotor-based VLEs. More specifically, it involves the theory that our perception of the world is determined by, or grounded in, our sensorimotor system; that our thoughts are a function of our body and its physical and temporal location [12]. The first study of embodiment commenced with the famous rubber hand experiment, where participants felt ownership toward a rubber hand even going to the extent of feeling pain when pain was inflicted to the rubber hand [13, 14]. Although not a requirement, the majority of embodiment work has been studied and implemented in highly immersive virtual reality (VR) settings and both, particularly the implementation, are typically neglected when considering non-VR (2D) environments that are implemented using standard computer equipment [15]. Research has found that simulating a realistic and fully connected human hand on an avatar (representing the user) in VR within a first-person perspective enhances the feeling of embodiment and plays a critical role in that sense of ownership, a concept of feeling a body belongs to oneself [16, 17]. Despite the necessity of embodiment for psychomotor skill acquisition, Ning et al. (2023) overlooked this fundamental aspect. This leaves an important gap; will coupling embodiment with pseudo-haptics enhance psychomotor skill performance? If the addition of the sense of embodiment, a fundamental aspect to psychomotor skill learning, enhances performance, then coupling embodiment with pseudo-haptics will improve psychomotor skill development in a simple and affordable manner.

1.2 Research Question and Objectives

This thesis work aims to answer the following research question: What effect, if any, does the sense of embodiment through the representation of a simulated hand have on performance and learning of a virtual drilling task when coupled with pseudo-haptics using a standard 2D computer display (visual cues), mouse (kinesthetic cues) and headphones (auditory cues)?

To answer the research question, three main objectives were outlined:

1. **Objective 1:** What does the representation of the simulated hand have on the sense of embodiment when coupled with pseudo-haptics and using standard computer equipment?
2. **Objective 2:** What effect does the sense of embodiment through the representation of a simulated hand have on the change in performance of a virtual drilling task when coupled with pseudo-haptics?

3. **Objective 3:** What effect does the sense of embodiment through the representation of a simulated hand have on learning the virtual drilling task when coupled with pseudo-haptics?

1.3 Aim and Hypotheses

The aim of this thesis is to understand the effect, if any, that the sense of embodiment, and more specifically the addition of a virtual hand (to represent the user's own hand within the virtual scene), has on a simple virtual drilling task on change in performance (i.e., skill acquisition) and learning when coupled with pseudo-haptics using standard computer equipment. It was hypothesized that if coupling embodiment with pseudo-haptics were to lead to enhanced performance, this work will lead to a cost-effective simulation that allows psychomotor training in the convenience of one's home using standard computer equipment.

To answer the main research question, participants will be asked to perform a virtual drilling task from a first-person perspective using standard computer equipment (i.e., computer display, mouse, and headphones). The study will include two sessions: i) a practice session and ii) a transfer test session. The practice session will determine whether the representation of the hand influences the speed of acquisition, measured through time to completion (H1) and number of attempts to complete the task (H2), and the sense of embodiment (H3) and participant's engagement (H4). After 24 hours from the practice session, the participants will be asked to undertake a transfer test to determine if the representation of the virtual hand has any effect on learning of the virtual drilling task (H5).

To accomplish this, five hypothesis statements were generated:

- **H1:** The embodiment group will take less time to complete the drilling task than the non-embodiment group.
- **H2:** The embodiment group will make fewer attempts to complete the drilling task than the non-embodiment group.
- **H3:** The embodiment group will have a higher embodiment score than the non-embodiment group.
- **H4:** The embodiment group will have a higher engagement score than the non-embodiment group.
- **H5:** There is a difference in the results of the transfer test between the groups.

Chapter 2. Literature Review

2.1 Overview

This chapter will serve as a background and inspiration behind this thesis work. It will cover important concepts and terminology that will be used for the remainder of this work. Moreover, it will outline the previous work that has examined embodiment, pseudo-haptics, and virtual drilling, which serves as foundation in this thesis. Refer to Appendix A for more information on how the literature review research was conducted.

2.2 Virtual Worlds and Virtual Learning Environments

With the growing popularity and advancement of technology, confusion, and lack of clarity on what makes up virtual worlds accompanied. To overcome these unclarities, Girvan (2018) redefined virtual worlds as:

> "Shared, simulated spaces which are inhabited and shaped by their inhabitants who are represented as avatars. These avatars mediate our experience of this space as we move, interact with objects, and interact with others, with whom we construct a shared understanding of the world at that time" (Girvan, 2018, p. 1099).

One of the main features of virtual worlds are avatars, the extension of user's body in the virtual world whereby they could use to interact and experience the world [18].

The term virtual environment could be thought of as a component of the virtual world where an 'environment' exists for the users within the world [18]. A virtual environment used for the purpose of education is known as virtual learning environment (VLE) and could be supported by a virtual world [18]. These VLEs could consist of serious games, that is, games whose primary purpose is education, and/or learning management systems (LMSs) such as Canvas [18]. While not all VLEs requires a virtual world (e.g., LMSs), they could be created in one to provide learners with a distinct learning experience.

2.3 The Sense of Embodiment

The term sense of embodiment, or ‘Embodiment’ in short, is used in many disciplines including philosophy, psychology, neurology, and technology. Over the years, this multidisciplinary term has gained various definitions, causing its meaning and conceptualization to depend on the context in which it is used [19]. This work will follow Kilteni et al.’s definition which states that the “Sense of Embodiment (SoE) will be used to refer to the ensemble of sensations that arise in conjunction with being inside, having and controlling a body” (Kilteni et al., 2012, pp. 374 - 375). In other words, an object is embodied if its properties are processed by the brain in the comparable way as those of one’s own biological body. The human’s brain is a very complex organ and if input signals from an artificial object are processed in a similar manner as one’s own, then the result is an illusion of feeling embodied to that artificial object [10].

2.3.1 Origin: What Inspired the Further Investigation of the Embodiment?

One of the early experiments that examined the basis of bodily self-identification and popularized the study of embodiment is the Rubber Hand (RH) experiment that took place in 1998 [13]. Ten subjects participated in this study, and each was seated on a small table with a divider separating their left arm from their view while a rubber hand of a left hand was placed in front of the participant directly where their left hand would have been. The participants were asked to look at the rubber hand in front of them while the experimenter synchronously stroked two paint brushes, one on the rubber hand and the other on the participant's real hand that is hidden from the participant’s field of view. The experiment showed that after being exposed to synchronous strokes of a paintbrush on both their own unseen hand and the rubber hand, the participants believed that the rubber hand became part of their body, even going as far as feeling the stroke of the brush on it when nothing was being done to their actual hand (Figure 2.1)[1]. This study shed light on this phenomenon and how multisensory interaction is sufficient to elicit embodiment. This experiment laid the groundwork to further studies and experiments that built on the original RH experiment trying to understand this phenomenon.

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[1] Visual demonstration: https://www.youtube.com/watch?v=sxwn1w7MJvk

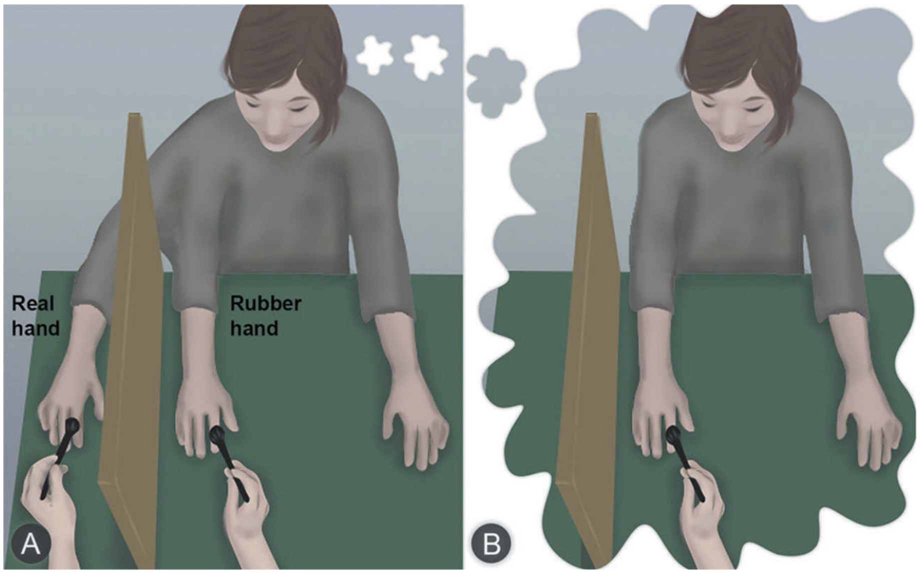


Figure 2.1. Rubber hand experiment procedure: (A) The participant watches the rubber hand being stroked with a brush while their actual hand is simultaneously being stroked. (B) The participant believed that the rubber hand is their own even when their real hand is no longer being stroked. **Reprinted from:** [20].

This RH illusion where the participants experienced a perceptual displacement toward the rubber hand instead of their own limb was later referred to as 'proprioceptive drift' [21] and its attribution involved multisensory interaction namely visual, tactile, the correlation of these modalities, and the perception of the location and movement of the body, otherwise known as proprioception [22]. Functional magnetic resonance imaging (fMRI) of the premotor cortex also reflected this multi-sensory interaction present in the RH experiment and as indicated self-attribution i.e., ownership of the rubber hand [23].

Researchers believed that the perceived multimodal proprioceptive drift observed is the cause of the feeling of ownership recorded [13, 24], however, a study by Rohde et al. (2011) determined that the feeling of ownership was only recorded when the synchronous stroking of the paintbrush was administered indicating that different multi-sensory mechanism are at play and measuring proprioceptive drift is not enough to determine ownership [25]. The RH illusion has become a classic experiment to demonstrate the sense of embodiment, and although it led to further research on embodiment, it does not address all aspects of embodiment and its complexity [10]. In sum, the RH experiment shed the light embodiment, ownership, yet it did not consider the other two subcomponents of embodiment, self-location, and agency, outlined by Kilteni et al. (2012).

2.3.2 Subcomponents that Elicit Embodiment

According to Kilteni et al. (2012), three subcomponents comprise embodiment, namely: i) self-location, ii) agency, and iii) ownership. These subcomponents became a subject of study to improve embodiment in virtual environments. In the upcoming sub-sections of this chapter, an in-depth exploration of each of these subcomponents is discussed. It should be noted that although each of these subcomponents are independent of each other, it is possible that one could affect another [10].

2.3.2.1 What is Self-Location?

Self-location refers to the sense of feeling located inside a body and where that body is located inside a space [26]. It is egocentric, meaning that it is self-centered and relies on one's own perspective, and is highly dominated by visual perspective as it relies on visuospatial perspective, especially first-person perspective view [27]. Self-location is self-conscious and is regarded as one of the most important subcomponents that elicit the sense of embodiment [10].

Self-location is often confused with other popular terms such as immersion or presence. Immersion is the state of being deeply mentally involved in a situation and it is highly dependent on the degree of sensory faithfulness in the virtual environment [28]. Whereas, presence is the state of existing or being present in a place [10, 28]. Although these terms might seem like self-location, they are defined differently. Unlike immersion and presence where the person feels as if they are present inside a space or the visual world, self-location is the feeling of being inside their own body in the real world, or an avatar in a virtual environment, the player's representation in that virtual world [29, 30].

2.3.2.2 What is Agency?

Agency refers to the ability to be in control of one's own body, to have voluntary and conscious actions of the body's movement [10, 26]. It is the least studied out of the three components of embodiment and depends on synchrony of the visuo-motor perception, i.e., the correlation between the voluntary movement and the visual perception of that movement. The lack of agency in a virtual body could inhibit the sense of embodiment [10]. Jeunet et al.'s work categorized agency in VR using two components: judgment and the feeling that have three principals: i) priority, ii) consistency and iii) exclusivity. 24 participants were recruited and embodied a virtual avatar in a first-person perspective and asked to perform pre-determined movement with the three principles either manipulated or not manipulated. The manipulation included: i) a delay was added between the movement and the feedback to manipulate the priority principle, ii) inversion the movement of distant fingers such as the index and ring finger to manipulate consistency and iii) have one finger not responsive to the participant movement to account for exclusivity principle. When these three principles were manipulated the sense of agency was decreased indicating the importance of these three principles in influencing the sense of agency in VR [31].

2.3.2.3 What is Ownership?

Ownership is the most studied of the three subcomponents of embodiment and refers to one's own self-attribution to a body, in other words feeling that an artificial object belongs to one's own body [10, 26]. Its strength depends on how realistic and similar the body host resembles the biological one, and it emerges from the combination of bottom-up (the influence of sensory information going to the brain) and top-down information (the cognitive process that influences sensory information). One can experience ownership of a body part or a full mannequin and avatar as long as it visually meets certain structural and morphological aspects and appears human-like [10]. These morphological and structural aspects may include skin colour, shape, and size. The degree of these morphological characteristics' visual realism influences the extent of ownership experienced [16]. Following the definition by Kilteni et al. (2012), all three subcomponents will be considered in this thesis work.

2.3.3 Visual Perspective and SOE

Research has shown that self-location is dependent on 1PP due to the importance of egocentric perspective (since self-location is self-localizing one's own body, a self-centered approach is a requirement, and this perspective is only possible in a first-person perspective where the view is from the 'eyes' of the avatar) [10, 32]. Depending on the position of the camera, two common visual perspectives exist: i) first-person perspective (1PP) referring to the gameplay view from the avatar's eyes and ii) third-person perspective (3PP) the player's view from being the avatar [33] (Figure 2.2). Each of these two perspectives offer a unique viewpoint. 3PP is better for awareness of the environment, while 1PP provides more accurate interaction due to the position of the avatar limb [34].

Figure 2.2. 3PP view (left) vs. 1PP view (right). **Recreated after:** [20]

Although both 1PP and 3PP could elicit ownership, ownership was shown to be stronger in 1PP compared to its counterpart [35]. On the other hand, agency does not seem to be dependent on visual perspective as both 1PP and 3PP were indifferent when inducing the sense of agency [35].

Maselli and Slater (2014) examined the effect of visual perspectives on self-location and ownership in VR. Three visual conditions were tested: i) 1PP with total overlap between virtual and real body, ii) 3PP with partial overlap between the virtual and real body and iii) 3PP with no overlap between the virtual and real body. In all conditions a cardboard tube was placed on 51 participants' legs to deliver vibration, creating a visuo-tactile stimulation. 1PP view was significantly higher at inducing embodiment than 3PP regardless of the bodily overlap. However, the authors found 3PP is able to induce embodiment if there is overlap between the virtual and real body, this is thought to be due to the influence ownership has on self-location where ownership was able to change the perceived self-location [36]. Lenggenhager et al. (2009) observed comparable results using multisensory inputs. In their study, 21 participants were exposed to visuo-tactile stimulation in a 3PP, observed the virtual body's back being stroked in front of them as they felt their own back being stroked simultaneously, they reported that virtual body was their own and mislocalized toward it [30]. Regardless, 3PP alone is not enough to cause embodiment as alone it does not elicit strong cues and might even break any existing embodiment [36, 37]. On the contrary, 1PP alone is able to evoke the sense of embodiment yet it is not a requirement [36]. In sum, 1PP was shown to have a greater impact on the sense of embodiment than its 3PP counterpart. Hence, 1PP was used as the visual perspective in this thesis work.

2.3.4 Technological Advances and SOE

Technological advancements enabled research questions to move from the 'how' to 'what' and allowed studying aspects of embodiment that would have been otherwise close to impossible [10]. More specifically, technology permits the researcher to manipulate the visual representation and multi-modal interaction of the avatar or a body part and its visual and body perspectives [38].

Experiments such as the RH experiment were replicated virtually using VR, augmented reality (AR) and mixed reality (MR) yielding similar results [39–41]. Yuan and Steed (2010) recreated the RH experiment using VR where 20 participants were seated on a small table with a head-mounted display (HMD) to show the virtual environment and a tracker wand in their right hand to control the avatar's right hand. The authors did not want to take the passive approach of the RH experiment where the hand just laid on the table, instead they wanted an active approach where the participants had to move their hand by partaking in a series of games. The first being the Simon game where the participants were required to point at the colours in the sequence that was shown to them and the second was a ball game where the participants had to drop the ball in the target hole designated by a ring. At one point during the ball game, a threat in the form of a lamp fell on the participant's virtual hand. The results of this experiment showed a similar response to the threat as those in the RH experiment where the participants felt the threat on the artificial hand as if it was their own [40].

Another recreation of the rubber hand experiment was conducted in AR by Nina et al. (2019). In their study, 30 participants were seated on the table and asked to wear a see-through HMD. The left hand of the participants was recorded and was displayed in the virtual environment acting as the artificial hand in the experiment. The results showed that the RH experiment is feasible in AR and that embodiment could be evoked to the virtual hand in the presence of a real hand and this embodiment was significantly stronger in the presence of synchronous input from both visuo-tactile stimulation, in the form of vibration, and visuo-motor simulation, i.e., hand movement [41]. The ability to replicate experiments digitally indicates that technology can induce embodiment. Many researchers such as those who conducted the RH experiment virtually opted to use highly immersive technologies such as VR, AR, and mixed reality (MR), that provide 3D viewing, ignoring 2D viewing [39, 41].

Multiple studies [42–44] have examined learning using 3D-based visuals in VR vs. visuals displayed on a standard 2D computer screen and found different results. Some work has found that learning and retention using VR yields better outcomes [42], while other work has found equivalent learning and retention in both VR and 2D computers [43, 44]. Madden et al. (2020) created a serious game simulation to educate students about the concept of moon phases and compare learning under different educational tools: i) VR; ii) computer-based desktop simulation and iii) hand-on activity (role playing without the use of technology). These authors chose the concept of moon phases because it is perceived to be one of the most challenging topics in astronomy. 172 student participants were recruited and randomly assigned a condition (56 using VR, 57 using computer-based desktop simulation and 59 in hands-on learning condition). All participants were asked to take a 14 multiple choice question pretest to assess their knowledge on the topic before they were assigned their learning condition. After completing the simulation, participants' knowledge was examined using a post-test also consisting of 14 multiple choice questions. The results showed that although participants' performance significantly increased when comparing pre-tests and post-tests results, there was no significant difference between the three different conditions. However, when participants were asked to rate which learning platform they preferred the most after trying all three, the majority of participants chose the VR experience [43]. Another study by Savvides (2018) investigated learning and retention of lab safety training under three different conditions: i) VR; ii) interactive simulation on a PC. iii) watch a video and read lab safety procedures. 108 participants were recruited and randomly assigned to one of the three conditions. A pre-test consisting of 10 multiple choice questions was administered to all participants before the start of the simulation. After seven days, the participants were invited back to participate in a post-test also consisting of 10 multiple choice questions. Out of the 109 participants, only 92 showed up to the post-test. The results showed no statistical difference in knowledge and retention between participants who learnt the material using VR and PC while both groups performed significantly better than those who watched the video and read the protocol [44]. However, Johnson-Glenberg et al. (2021) indicated that when including embodiment, both VR and 2D displays outperformed their low embodied counterparts [15]. These authors were also comparing the performance in a VR simulation vs. 2D-based simulation on a PC while performing a simulation game of capturing butterflies to educate learners about natural selection. 179 participants completed the study successfully. All participants were asked to complete a pre-test before participating in the simulation game where they were asked to capture at least 20 non-poisonous butterflies before the time ran out after they were randomly placed in a group: high embodiment VR, High embodiment 2D-based simulation on a PC, low embodiment VR, low embodiment 2D-based simulation on a PC. The high embodiment condition allows the participants to use the mouse (PC) or controller (VR) to manipulate content whereas in low embodiment participants watched a playable video. After the simulation, the participants completed a post-test and after a week participants came back for a follow up test. The results showed that participants in the high embodiment group performed significantly better than those in the low embodiment group. Moreover, although participants in high embodiment VR performed better than PC, the results were not significant for the platform since low embodiment VR performed worse between all groups [15]. Regardless, 2D displays are currently more accessible and convenient to the general population compared to high immersive VR, hence standard computer equipment will be used for the purpose of this work.

2.3.5 SoE and Psychomotor Skills

Psychomotor development is fundamentally the study of behavioural development and contrary to many beliefs, it is inherently psychological [11]. Any movement depends on the status of the body to generate, exploit, and control forces. Without being bodily present, one cannot generate, control, and exploit any voluntary movement and in turn cannot acquire any new skills [11]. Hence, the sense of embodiment is fundamental to psychomotor development [11]. Interestingly, the strength of embodiment is consistently related to bodily processing of multisensory information in the brain, namely in the motor cortex, whose primary function is to general voluntary movement [16, 45].

2.3.6 Measuring Embodiment

Different methods have been employed to measure the sense of embodiment, namely physiological and behavioural responses, and self-reported questionnaires [10, 26]. Some of these physiological and behavioural responses include heart rate in response to a threat, change in response and reaction time, skin temperature change, and neural activity in various brain areas [26]. However, most measuring methods usually examined one of the subcomponents of embodiment and not as embodiment. These measures may not always reflect nor correlate with the full dimensions of embodiment [10, 26].

Since embodiment is a personal experience, the use of self-reported questionnaires is a common method of gauging embodiment. Multiple questionnaires have integrated the three subcomponents of embodiment, self-location, ownership, and agency, leading to a standard questionnaire that best captures the degree of embodiment elicited. Eubanks et al. (2021) looked at pre-existing questionnaires, indicating that there is a need for a standard questionnaire that encompassed all three subcomponents of embodiment. They created a preliminary questionnaire, containing 10 questions scored on a 5-points Likert scale, and validated in two studies containing 30 participants for the first study and 14 participants for the second study (originally, they were planning 45 participants each but due to COVID-19 pandemic, they had to stop recruitment). Despite their limited data, they were able to find significance and validate their preliminary questionnaire [46] . However, the lack of sufficient data to validate the questionnaire withstood us from using this questionnaire in this study. Gonzalez-Franco and Peck originally created a preliminary standardized questionnaire in 2018 containing 25 questions on a 7-point Likert scale [47]. Initially, these authors did not validate their questionnaire in their 2018 paper, however, in 2021 Peck and Gonzalez-Franco published their validated 25 questions questionnaire cutting it to contain 16-items instead based on data from over 400 questionnaires collected from nine experiments [48]. The final questionnaire still accesses the different subcomponents of embodiment making it the ideal questionnaire, and thus was used in the study described in this thesis.

2.4 Multimodal Interaction & Cross-Modal Perception

Humans perceive and interact with the world through their senses. Although humans are visual beings, they also rely on other forms of information to understand the world around them. The source of this information could be external (e.g., visual, auditory, haptic) or internal (e.g., vestibular or proprioceptive cues) [49]. Multimodal interaction refers to the interaction of different senses and how their interaction affects perception, whereas cross-modal refers to the influence one sense has on the perception of another [50]. The interaction and overlap of this different sensory information provide humans with an inclusive and wholesome experience of the world around them. Humans are constantly exposed to sensory information from their environment and one's cognition is determined by, or grounded in, one's sensorimotor system; that one's thoughts are a function of one's body and its physical and temporal location [12]. Similarly, multimodal interaction in virtual environments influences the user's perceived embodiment and ultimately their performance [49, 51].

A large body of research has examined the interaction of the different sensory components notably visual and auditory but also visual and haptic and auditory and haptic interactions. Each of these senses can interact together and influence each other to make sense of the world and surroundings [9].

2.4.1 Visual and Auditory Interaction

Multiple illusions can be created when visual cues and auditory cues interact in both real world and virtual world. A real-world example is the 'ventriloquist effect' where images can be localized with sound even when the sound is not coming from the object [52]. Another real work example is the popular McGurk effect where the auditory component interacts with the visual component of another sound creating the perception of another sound [53]. The Bouba-Kiki effect, a popular McGurk effect, demonstrates the tendency for people to choose the round shape for ‘bouba’ and an angular visualization for ‘kiki’ when asked to match the sound to the shape [54]. Interestingly, the Bouba-Kiki effect could also be induced using sound and touch instead of vision [54]. In a study, where 122 participants (consisting of 80 fully sighted and 42 visually impaired participants) were presented with one of four bags each containing a variation of two shapes, one round and the other spiky. when the researcher calls out either ‘bouba’ or ‘kiki,’ participants were asked to choose which shape they thought matched the word without looking inside the bag. After making the selection from each of the four bags, the researcher asked the participants to give a reason for their choices. Although the effect was significantly weaker in visually impaired participants, both groups experienced the Bouba-Kiki effect. This finding indicates that the Bouba-Kiki effect is not entirely independent of vision because even in haptic-auditory interaction, visual imagery seems to play a role [54].

Visual and sound cues can influence each other in virtual environments as auditory cues can affect the perception of visual fidelity, realism and performance both positively and negatively depending on the sound condition used [55]. Sound was shown to attract the participants attention away from visual stimuli leading to a reduction of cognitive processing. Moreover, adding the sound of footsteps while an avatar is walking makes the animation look smoother [56].

2.4.2 Visual and Haptic Interaction

Apart from the famous RH experiment, another famous visual-haptic interaction illusion is the size-weight illusion. More specifically, Cross and Rotkin (1975) observed that by changing the volume of two objects, 20 participants perceived the larger object to be lighter than the smaller one even when both objects had the same weight [57]. This illusion could work when using somatosensory cues alone or when combined with visual cues and was later shown that the speed of the object also influenced its perceived weight as faster objects were perceived as lighter [58–60].

In virtual environments, the use of visual cues could provide the impression of haptic cues, a field referred to as "pseudo-haptics." Pseudo-haptics can also be achieved using audio cues although auditory cues are less studied and hence less used than visual cues to elicit this illusion (more on pseudo-haptics in Section 2.5). The perceived hardness was shown to be altered using visuo-tactile interaction in VR [61]. In an empirical study conducted by Matsumoto et al. (2018), the authors used force-inducing gloves and visual representations to manipulate the stiffness of virtual objects observed using an HMD in VR. The gloves used contained piano wires that constrained the fingers allowing the participants to feel the reaction force when squeezing the virtual object. At the same time, the participant saw the object deform as they moved their fingers [61]. Moreover, resistance was virtually simulated by Pusch et al. (2009) using visual cues. These authors wanted to create the sense of force to 13 participants' hands as they virtually moved it in space. They proposed HEMP, signifying Hand-displacEMent-based pseudo-haptics, which provides the perception of haptic resistance by altering the visual representation of the participant's user virtual hand in AR. The results show that participants were able to perceive the flow resistance sensation [62]. In general, the perceived object properties are improved when virtual and haptic cues interact.

2.4.3 Auditory and Haptic Interaction

Audio-haptics interaction is significantly less researched compared to visual-haptics interaction, yet this interaction still exists both in the real world and the virtual environment and hence it is worth mentioning [9]. Prior research has shown that auditory cues could be sufficient to provide information regarding object size, property, and events [63, 64]. Sound waves travel through different materials at different speeds, causing distinct vibrations when the material is stroked hence a different sound is produced [65, 66]. Sound cues were also shown to convey information about materials' texture, more specifically the sound the material makes when touched the material [67]. How sound affects texture was demonstrated in the 'parchment skin illusion' where 13 out of 17 participants' perception of the wetness and dryness of the hand was altered when researchers attenuated and accelerated the sound frequency of two hands rubbing against each other [68].

Auditory and haptic interactions can also occur in a virtual environment. Nordahl et al. (2011) asked their 15 participants to identify different surfaces under different conditions: i) haptic only using haptic shoes (shoes with haptic transducers), ii) sound only, iii) both sound and haptic cues. The results showed that participants were able to identify objects' identity solely using auditory cues without the use of haptic cues, while haptic cues were best at identifying the hardness of the objects [69]. However, when combining both there was no significant increase in object identification [69]. Other studies have shown that sound is able to influence stiffness and force perception in virtual environments [70, 71]. However, when coupled with visual cues, sound did not contribute to the force perception but the perceived realism and presence of that force [72].

2.4.4 Visual, Auditory and Haptic Interactions

Research has found that the addition of different cues improves overall motor learning such as virtual throwing task performance even when these modalities do not add any additional information [73]. This increase in task learning was believed to be due to the overlap between cues. This overlap is thought to either provide the additional information to the task or can be totally overwritten by the most dominant modality when the same information is added [74]. Processing speed was shown to be inversely proportional to the addition of modalities where trimodal (visual, auditory and haptic) show shorter processing time than when bimodal or unimodal was used and bimodal provided shorter processing time than unimodal stimuli [75].

Most of the research has focused on interactions between two modalities, yet several researchers have incorporated some trimodal interaction and integration in their research. For example, George et al. (2020) examined the interaction of trimodal (visual, auditory, and haptic) stimuli in a virtual environment. They created a VR game called “Floor is Lava” where the participants pretend that the floor of a room (could be the kitchen, or the living room) is lava and the player must reach the safe zone by maneuvering through the room without touching the ‘lava’ i.e., floor. 33 participants were provided with noise cancelling headphones (auditory cue), a head-mounted display (visual cue) and controllers that vibrate if the participants touched the lava (haptic cue). When tested under different modal conditions, unimodal (just visual), bimodal (auditory and haptic without visual) and trimodal, participants touched the lava the least when all three modalities were in use even when the visual cue played the most critical role in the study [76]. Another study by Wei et al. (2022) recreated haptic signals using visual and auditory stimuli. To accomplish this, they created an algorithm, which they referred to as audio-visual-aided haptic signal reconstruction (AVHR), that computed the visual and auditory feedback of the texture of the material to reconstruct the object's haptic signal. They found that the ten participants were not able to differentiate between the haptic signal created by the AVHR compared to the real haptic signal of the material [77]. The study by Wei et al. (2022) is an example of using cross-modal interaction to recreate the sense of touch in virtual environments void of haptic devices, a field that became known as 'pseudo-haptics'.

2.5 Haptics and Pseudo-Haptics

To simulate psychomotor-based tasks in a virtual environment, an accurate representation of the sense of touch is required [3]. However, simulating the sense of touch in virtual environments is challenging since it requires the accurate replication of many variables such as pressure, temperature, vibration and texture [78].

The sense of touch falls under the field of haptics, which is further subdivided into kinesthetic feedback and cutaneous feedback [9]. Kinesthetic feedback refers to the feedback related to motion and sensation from muscles, tendons, and joints and sensation originating from them such as force feedback [9]. Whereas cutaneous feedback is more dermal and includes tactile sensation such as pressure and vibration and other sensations such as pain and temperature [9].

With the use of haptic devices, it is possible to induce some haptic feedback such as vibration [79], pressure [80], and temperature [81]. Haptic devices can be divided into three major categories: i) grounded, which is then subdivided into graspable and touchable, ii) hand-help such as controllers, which can be subdivided into direct or indirect actuation or iii) wearable devices that is include exoskeletons, finger-worn and arm-worn [8]. Grounded devices cannot be worn around the body, and since they are limited in terms of size, some of these devices can become bulky and heavy (Figure 2.3a). The graspable types are known for their kinesthetic feedback, although some could also provide cutaneous feedback in the form of vibration and are able to provide an accurate wide range of force. Touchable devices provide mostly cutaneous feedback in the form of vibration, ultrastatic or ultrasonic feedback. These devices do not require active and accurate movement, they just allow the user to tacitly interact with the objects. Hand-held devices can be picked up and held in the hand without the use of any straps (Figure 2.3b). Since these devices cannot be worn, they provide limited movement and are able to provide both kinesthetic feedback and tactile feedback. Wearable devices are haptics devices that can be worn on the user's body. They provide the user with kinesthetic feedback directly on the user's bodies. The main drawback of these devices is that the users will not only feel the desirable haptic feedback caused by the simulation, but also the force of where the decision is strapped on the user's body (Figure 2.3c).

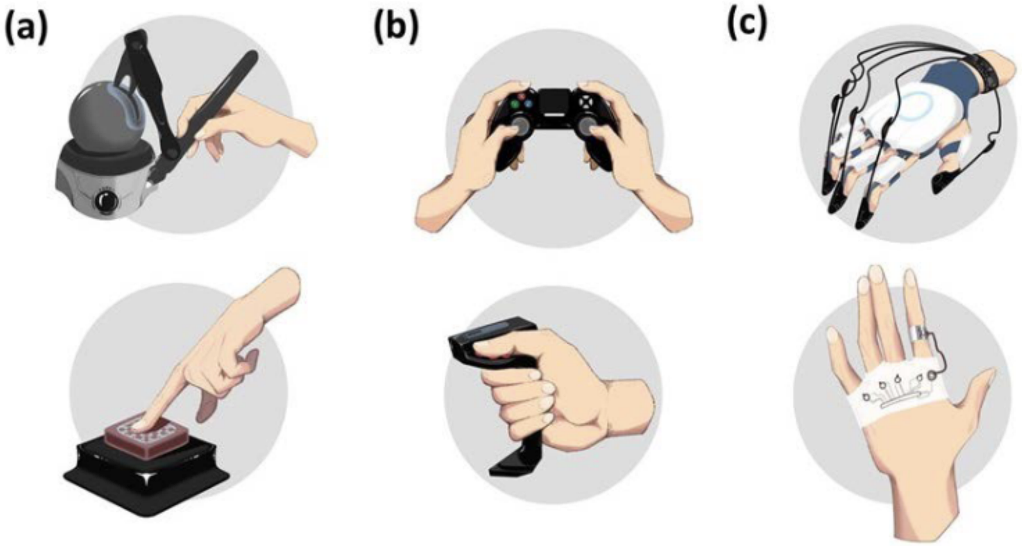


Figure 2.3. Example of haptic devices: a) grounded; b) hand-held; c) wearable devices. **Reprinted with permission from:** [8]

However, most of these devices are not always accessible at the consumer level due to cost limitations and hardware size [3, 82]. The development of these haptic devices requires manufacturers to consider differences in the user body size, such as height and arm size [8]. One of the major challenges to employing haptic devices is their very high market cost limiting their accessibility to the general public who might not be able to afford them [83]. Another challenge that these devices pose is storing and using them in limited spaces due to their size [8]. Some of these are large and heavy making transporting them and using them in tight spaces difficult.

To overcome the shortage of these haptic devices, the field of pseudo-haptics has emerged. The term ‘pseudo-haptics’ refers to the simulation of haptic sensation without the use of haptic devices by “tricking” the mind into thinking there is a haptic sensation (e.g., a haptic illusion is created) using cross-modal interactions [9]. One way to induce pseudo-haptics is using the control/display (C/D) ratio to elicit haptic feedback using visual stimuli. The C/D ratio is a distortion technique where ‘C’ represents the input displacement usually done by the user and the ‘D’ represents the resulting visual displacement on the screen. The discrepancy between these two variables can create an impression of an object's property such as force, weight, friction, and much more like roughness, and viscosity [84]. Lécuyer et al. (2004) used the C/D ratio in their study to simulate texture, more specifically a “bumpy”, a hole or a flat surface when ten participants moved their 2D computer mouse over the white disk to identify the shape hiding under it for a total of 57 trials. Mathematical profiles such as linear, polynomial and gaussian, were used to create the impression of the bump and hole along with the modification of the C/D ratio. The results of their study show that participants were highly effective at identifying the bump and hole shape under the white disk with the bump surface being slightly higher than the hole. The participants were less effective at identifying the flat surface correctly (no shape under the white disk) [85]. Rietzler et al. (2018) were able to visually change the perceived weight of an object by changing its perceived inertia whereby heavier objects require more time to accelerate and slow down [86]. Kang et al. (2019) also used pseudo-haptics by visually manipulating the distortion between the participant’s arm and the avatar’s limb to create force feedback in the form of drag force during a swimming simulation [87].

Although less studied than visual stimuli, pseudo-haptic can also be elicited using sound feedback. A study by Kaneko et al. (2022) employed sound feedback more specifically, by manipulating sound response delay, pitch (frequency) and loudness in response to button click, they created the perception of object heaviness without the use of any visual feedback. Lower pitch and loudness are often associated with the perception of heavy objects. Using their personal computer to participate in the study, the 131 participants were asked to rate the heaviness of the two squares displayed on their screen. By clicking on each of the two squares buttons presented sequentially on the screen, one of the sound conditions was played. The sound conditions included two frequencies: i) 200 Hz, and ii) 400 Hz accompanied with one of five delay conditions: i) 0 ms, ii) 100 ms, iii) 200 ms, iv) 300 ms, and v) 500 ms. The sound played had one frequency and one delay condition randomly assigned to each of the two buttons. A control condition with no sound was also included. In total, there were 11 different sound conditions (2 frequency × 5 delays + one no sound condition). Each of the 11 conditions were repeated 4 times for a total of 44 trials. After the sound condition was played from the two squares, the participants were asked to compare the two squares and rate which one was heavier using a 5-point Likert scale ('1' being the square on the left was heavier and '5' being the square on the right is heavier). The results showed significant differences between the two frequencies with the lower frequencies being perceived as heavier. Moreover, there was significance between the delay times where the participants perceived a stronger heaviness sensation when the sound was more delayed. However, no significant difference was found between frequency and delay interaction. In a similar experiment, Kaneko et al. (2022) compared the two square buttons' perceived heaviness this time by manipulating the loudness instead of frequency. They found that louder sounds were perceived significantly heavier than when sound was played at low loudness level. Similar to the prior experiment, delayed conditions yielded significant results and no significance was found when comparing loudness and delay conditions interacted.

Interestingly, the offset of the sound (when the sound concludes) seems to play a critical role in the perceived heaviness because when in comparison to onset sound (initiation of sound), it yielded significant results. In sum, by changing the visual and/or sound stimuli, researchers were able to simulate the perception of haptic feedback without the use of expensive haptic devices [88]. The use of pseudo-haptics may lead to a more affordable alternative for expensive haptic devices and hence it is worth investigating its effect when coupled with embodiment.

2.6 Application of Drilling in the Healthcare Field

Drilling is commonly used both in common everyday tasks such as mounting a curtain, tightening loose screws, and hanging family pictures, and in professional fields such as construction (e.g., carpentry), and healthcare. In the healthcare field particularly, drilling is a common practice used in different surgeries such as dental [89], orthopedic [90], and in needle insertion including Intraosseous (IO) infusion [91]. Multimodal interaction such as haptic feedback in the form of force and vibration and drilling sound play a critical role in successful drilling tasks [92]. Sound feedback is one of the main cues often utilized in drilling. Information from the drilling pitch, volume or frequency inform the user about friction, force, location of the drill bit, and density of material being drilled [93]. For example, to perform an IO infusion, a procedure that allows the delivery of fluids through the bone marrow to the proximal tibia and is often performed by paramedics, who must know where the infusion needs to be made, they will rely on their visual and haptic cues to palpate the anterior tuberosity of the proximal tibia to properly locate the insertion site. Once located, they will use a medical drill to penetrate the bone into the marrow. With the lack of visual cues on how deep they need to drill, the paramedic needs to rely mainly on auditory cues and haptic feedback to identify how much further they need to drill. As the drill reaches the bone marrow, a more spongy material in comparison to the hard bone cortex, the paramedic will feel a loss of resistance (haptic feedback) and drilling pitch changes (auditory feedback) signalling to stop drilling [94, 95]. A similar strategy can also be seen by surgeons for orthopedic procedures who utilize the pitch of sound while drilling to detect the density and resistance change to cease drilling to avoid potential patient injuries [93]. Likewise, in dental surgery where visual cues are restricted, dental surgeons rely on other cues such as haptic feedback to know when to cease drilling [96].

These surgical drilling procedures require a considerable amount of training to perfect and practicing these skills in a realistic and safe manner is challenging. Simulation provides a safe, effective, and reliable environment to recreate and practice these surgical drilling procedures without risking any patient injury. Simulation also allows the user to manipulate variables, make the practice more challenging or to investigate situations otherwise rare or close to impossible in real life. Due to the importance of drilling procedures in the healthcare field, the simulation used in this work will simulate a virtual drilling task.

2.7 Related work

This thesis work built on prior work conducted by prior graduate students in the maxSIMhealth Lab. In this section, these related works will be highlighted. Melaisi et al. (2018) looked at the impact of sound (comparing contextual, i.e., a sound related to the task being performed, such as the drilling sound, including the changing pitch, as the drill moves through the piece of wood, and non-contextual, a sound no related to the task's sound and could include white noise, music, or a static sound) on haptic feedback performance and fidelity. They developed a virtual drilling scenario using Unity3D engine that ran with two haptics devices: i) Novint Falcon and ii) Geomagic Touch 3D stylus, two grounded haptic devices that simulate texture, recoil, and momentum. Four auditory conditions were used in the study: i) no sound; ii) drilling sound, iii) white noise and iv) classical music. 15 participants were randomly assigned one of the haptic conditions and their task was to drill two depths: i) 2 cm though a virtual wood or ii) 5 cm though a virtual wood and metal. One sound condition and drilling depth were randomly presented during each trial for a total of 24 trials (two drilling depth × four sound conditions; repeated three times). average completion time and depth accuracy (drilled depth - target depth) acted as the dependent variables of the study. The results showed no significant difference between the two haptics devices and no significant difference between the auditory stimulus, indicating that haptic devices and sound stimuli did not affect performance. However, a significant difference was observed in the drilling depth accuracy between 2 cm depth vs 5 cm depth as more participants were more accurate drilling 5 cm than 2 cm. On the other hand, completion time between the two drilling depths showed no significance [97]. The work of Melaisi et al. (2018) used haptic devices to simulate haptic cues in their drilling task. As discussed in previous sections, most haptic devices use is inconvenient due to them being costly and require large storage space, whereas pseudo-haptics brings a cheaper and convenient alternative.

Ning et al. (2023) examined the use of pseudo-haptics in a simulated drilling task using a multimodal approach. They hypothesized that combining auditory feedback and kinesthetic stimuli, using basic computer equipment such as 2D mouse, a monitor, keyboard, and headphone can simulate the experience of drilling without the use of haptic devices. Using the Unity3D engine, a drilling scenario was created in which 13 participants were asked to drill 12 cm into a virtual piece of wood under different two visual, two movement conditions and three auditory conditions. The visual conditions included: i) visual cues (i.e., top view) and ii) no visual cues (i.e., back view). The two movement conditions included: i) manipulating the virtual drill using a 2D mouse (include kinesthetic feedback); ii) manipulating the virtual drill using a keyboard via key presses (no kinesthetic feedback). Three auditory conditions were used for this study: i) no sound; ii) contextual (or dynamic) sound, and iii) non-contextual (or static) sound. The participants were asked to perform the drilling task 36 times, each trial had one visual and one auditory condition randomly administered (two visual × two movement × three auditory; repeated three times). The drilling depth was recorded and served to calculate the drilling depth error (drilled depth - target depth) that acted as the dependent variable in this study. The results showed that pseudo-haptics in the form of kinesthetic stimuli is an essential factor to simulate the drilling experience. In addition, they found a significant difference between the "keyboard control" vs. "mouse control" where "mouse control" was found to yield more accurate results. However, they found no significant difference between the three sound conditions [5]. As previously stated, Ning et al. (2023) overlooked the importance of embodiment when simulating psychomotor skill, hence in this work, embodiment and pseudo-haptics were coupled to determine their effect on performance and learning.

2.8 Summary

Embodiment, the sense of belonging and controlling a body, consists of three sub-components: i) self-location, which is the sense of feeling located inside a body and how that body is in space; ii) agency, which represents the ability to voluntary control one's own body; and iii) ownership which refer to self-attribution to one's body. Embodiment plays a critical role in psychomotor skill development since any voluntary movement requires one to feel embodied. While most of the embodiment work is based in VR environments, particularly through the representation of an avatar limb, usually a hand, little work has considered embodiment using 2D-based computer simulation. On top of being embodying an avatar, being able to interact haptically with the environment is essential for a successful and effective psychomotor-based simulation. Pseudo-haptics provides a cost-effective 'middle step' without the use of costly haptic devices using a multi-modal interaction between visual and auditory cues.

Chapter 3. Virtual Simulation Development

3.1 Overview

This chapter will underline the method apparatus by outlining the development of the virtual simulation environment used to simulate the drilling operation. More specifically, it discusses the virtual simulation design and the reasoning behind all the additions and changes to the base simulation, originally constructed by former graduate student, Guoxuan Ning, to meet the objectives of this study. This work was a collaboration between me, who conceived the required changes (described in this chapter), and communicated them with Cody Jensen, an undergraduate student in the Game Development and Interactive Media program at Ontario Tech University. He was instrumental in the implementation of these required changes.

3.2 Unchanged Elements from the Original Virtual Simulation

The original virtual simulation, developed using Unity3D game engine, contained a scene of the block of wood and the drill (Figure 3.1). It also included the audio files used in the original study, the kinesthetic feedback and the mouse and keyboard controls. From the multiple audio files provided, only the contextual sound was used. Ning et al. (2023) determined that mouse control was more accurate and thereby was kept unchanged, and since the objectives of the study required the pseudo-haptics response, the kinesthesis feedback conjoined with the mouse also remained unchanged. The mouse controls are as follows: the left button activates the drill, moving the mouse will move it toward/away from the block of wood, and releasing the left button deactivates it.

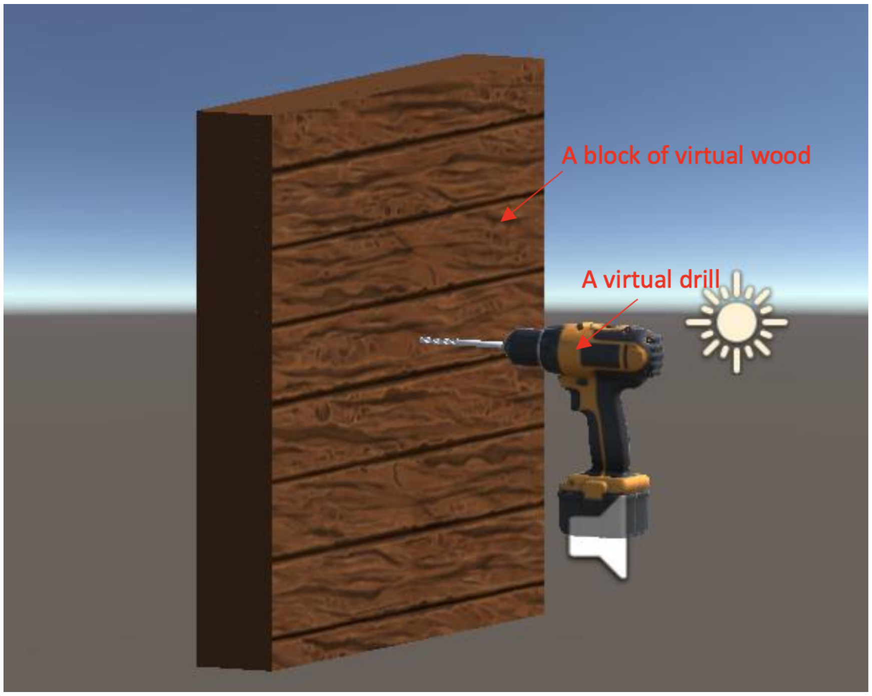


Figure 3.1. The Unity3D scene showing blocks of wood and drill.
Reprinted from: [5].

The contextual auditory stimuli were recorded using a Tascam DR 100 handheld field recorder. It was placed 90 cm away from the wooden block and while drilling into a 15 cm wooden block divided into 40 layers and connected back together. By doing so, the different depth of the block will be recognized in the audio recorded. The drilling was done using a Tacklife PCD05B drill with a drill bit with a total length of 15 cm and a diameter of approximately 0.635 cm.

To recreate the same experience virtually, the wood block, a 3D rectangular object with a graphic wood texture, was also divided into 40 segments with a trigger added to each layer where a change of sound occurs to represent the change in depth (Figure 3.2).

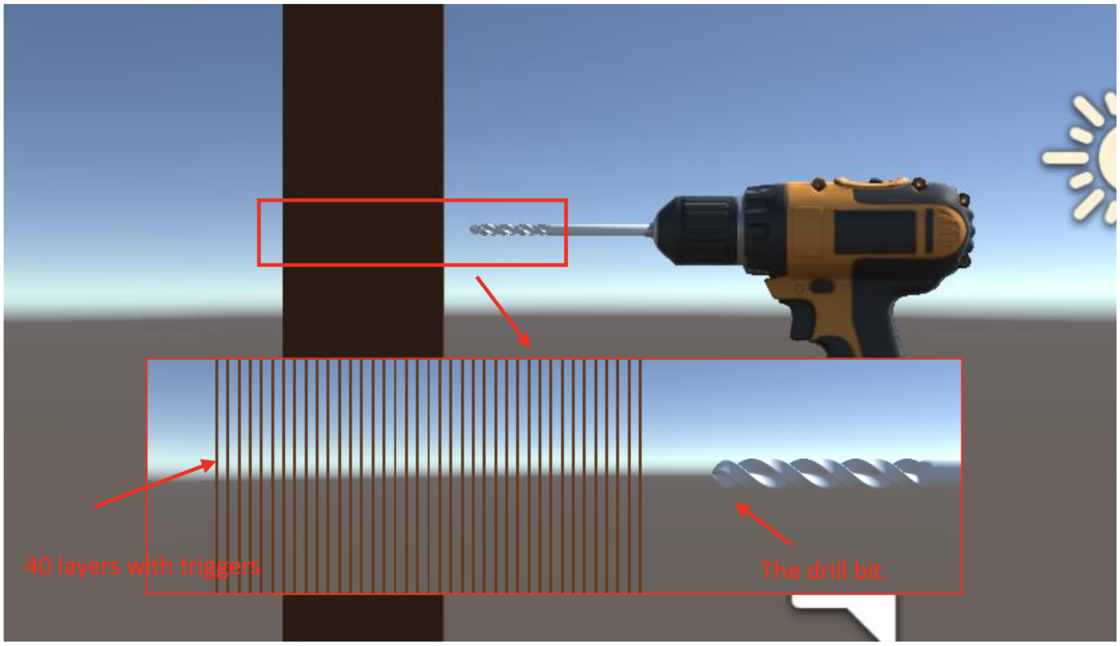


Figure 3.2. Virtual wood block made up of 40 layers of the wooden block with triggers. **Reprinted from**: [5].

3.3 Addition of the Virtual Simulated Hand

To answer the research question and based on the definition of embodiment discussed in the previous chapter, to achieve any sense of embodiment, a visual representation of one's body or part of the body (limbs being the most popular) is recommended [10]. Research has found that simulating a real human hand on an avatar, the "body" that represents the user in a virtual space, enhances the feeling of embodiment in VR [17]. Therefore, an addition of a virtual hand was a requirement. A package was purchased containing a hand model and edited to portray it holding and manipulating the drill to be added to the serious game (Figure 3.3). Additionally, Seinfeld & Müller (2020) have found that a discontinuity between the hand and the rest of the body could be detrimental to the sense of ownership and embodiment [16], hence an arm connecting the hand was also included.

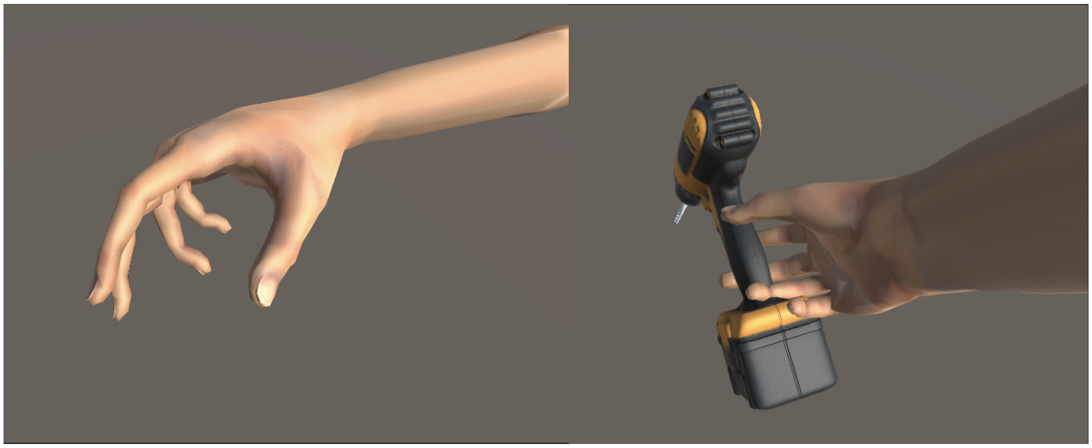


Figure 3.3. Edited Hand package to represent hand holding a drill.

3.3.1 Skin Tones

Since the purchased package came with only one default skin tone, and the purpose of the study is to investigate embodiment into the virtual body, a diverse variety of skin tones was necessary. To establish a palette of colours, 'The SIMS 4's' skin tones were used. 'The SIMS 4', one of the best-selling PC games with over twenty million players worldwide, tries to simulate real life experience and offer a high degree of customization to their avatars. Players also have the potential to make custom content by modifying files creating designs of their own [98]. With this freedom of customization, this game was determined to be the ideal choice and thus, five natural colour palettes were chosen to serve as the virtual hand's skin tones (Figure 3.4).

Figure 3.4. Five skin colours palette where participants could choose the virtual hand's skin tone.

3.4 Adding Realism

To account for a better view and increase the realism of the simulated task, the scene was changed from its original design where a standing block of wood is handing in the air in front of a drill to a more realistic workbench with a piece of wood laying on top of it (Figure 3.5). The purpose of changing this design is to enhance presence in the virtual environment by adding more realistic visual representations of woodwork tasks. In multiple procedures on how to drill a hole into wood, all the pictures were taken on a bench with a wood laying on top [99–101]. Realizing that it is customary practice to drill on a bench, a new scene was created to account for this more realistic visual representation. Although presence does not cause embodiment since they act on the environment rather than the 'avatar's' body, their inclusion does aid embodiment by making the environment more realistic and help with spatial representation that is needed for self-location, one of the subcomponents of embodiment [10].

Additionally, Martin et al. (2020) examined the impact missing fingers has on realism and presence in VR and found that particularly missing dominant fingers decrease presence and show high phantom pain ratings, a pain rating associated with missing body parts. Based on Martin et al.'s study, a simulated left hand was also added to the virtual drilling simulation. Although the study examined missing fingers, whereas in the study in this thesis includes a hand, Martin et al. (2020) described that other studies did find that a missing hand also influences embodiment, especially body ownership [102]. To avoid such phenomena occurring, a left hand was added to the scene (Figure 3.5).

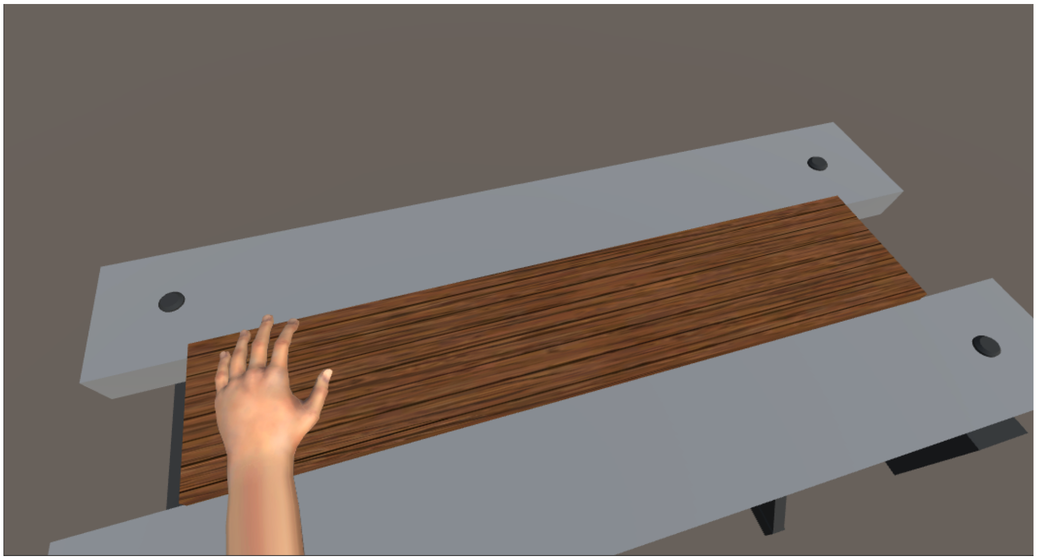


Figure 3.5. Workbench and left hand were added to the scene to increase realism and presence.

Moreover, it was necessary to change the camera view to account for the definition of embodiment, especially since self-location highly depends on the visual perspective, to be induced (Refer to 2.3.2.1 and 2.3.3 for more information). Originally, Ning et al. (2023) had the player view either as top view or back view (Figure 3.6). These views would not have been ideal for embodiment where the perspective of the simulated body hand should be in a first-person perspective to be perceived as an extension from one's own body [10, 26].

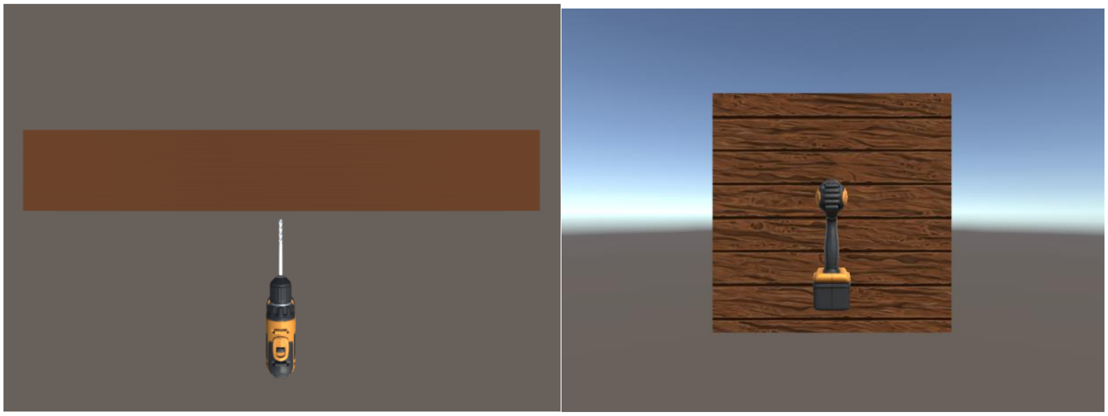


Figure 3.6. Original study's top view (left) and back view (right).
Reprinted from: [5]

To allow this, the player must perceive the virtual hand in the location where their real hand would have been if they were to perform drilling themselves in real life. To account for this, we needed to change the view to a first-person perspective such that the view is positioned where the player's eyes would be located while considering the position of the hands (Figure 3.7).

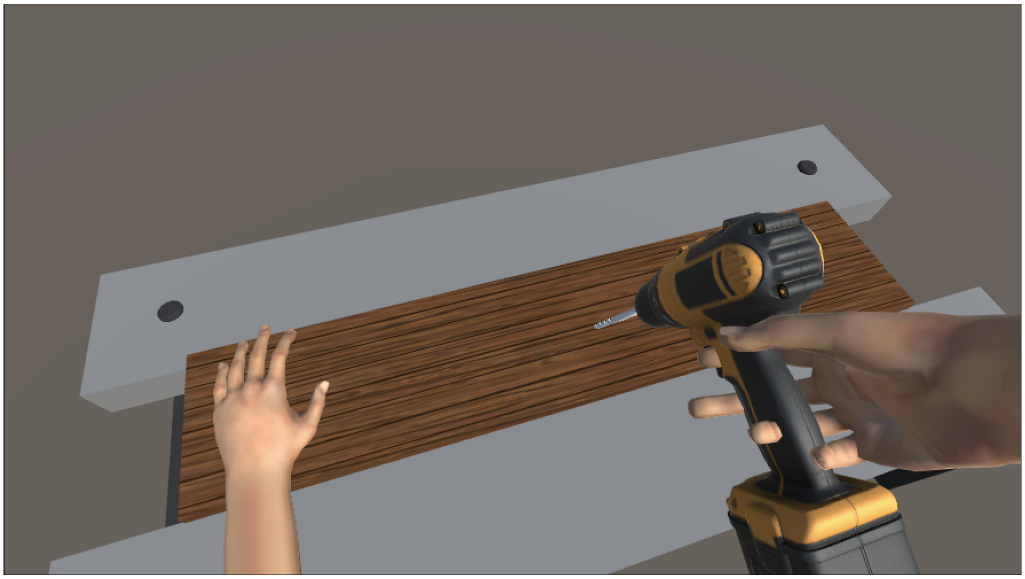


Figure 3.7. New camera view in first-person perspective.

Additionally, shadows were added to the hands and the drill to elicit a more realistic experience when drilling (Figure 3.8). It not only allows the user to make spatial relationships between objects, but it also provides a greater sense of depth to the scene [103]. The changes in the scene and the camera view both allowed for a more realistic drilling experience.

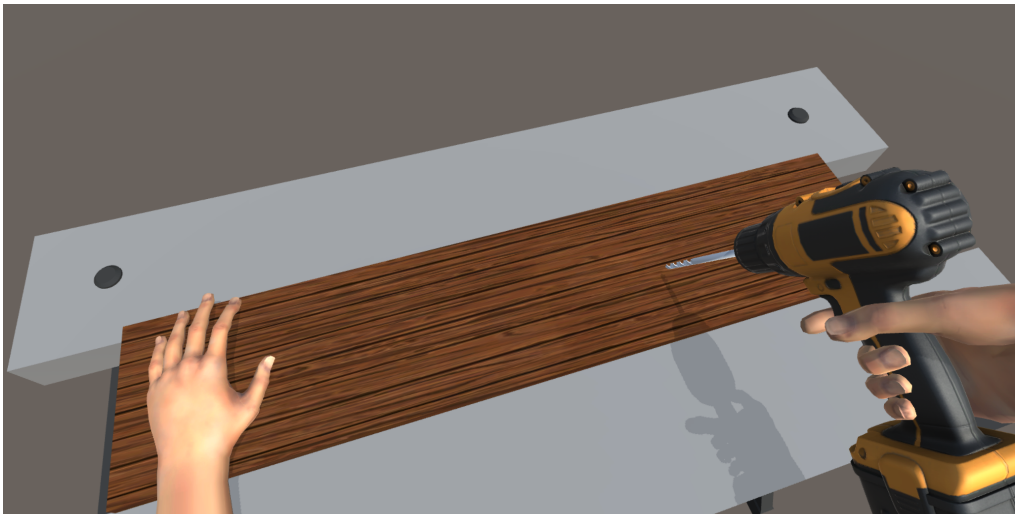


Figure 3.8. Addition of shadows to create a more realistic experience.

3.5 Detecting Performance Proficiency

The performance curve was first used to explain life cycle thinking by Charles Handy in 1995 then later applied by Whitney Johnson in 2012 to illustrate competence development [104, 105]. This sigmoid curve, otherwise known as the s-curve, is thought to follow a sigmoid shape, where the learner starts with a low performance and then slowly their performance increases until it plateaus, where performance remains stagnant (Figure 3.9).

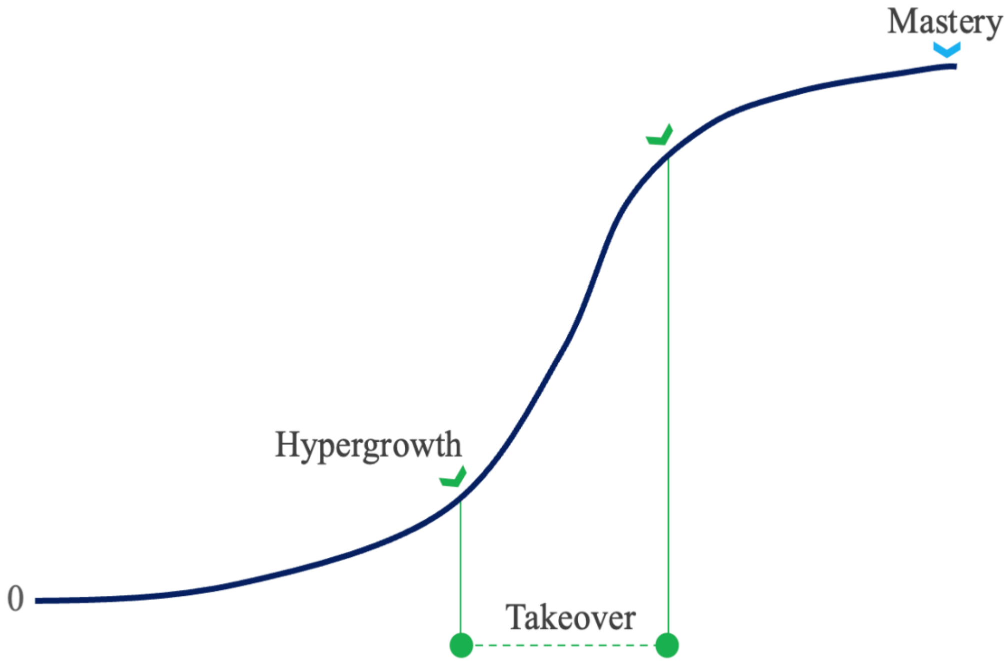


Figure 3.9. Performance curve: it illustrates the sigmoid curve the learners undertake to go from being a novice with a low-performance rate to a constant high-performance rate as they gain expertise. **Recreated after:** [106]

Two approaches were considered to determine proficiency and deemed the task complete: i) setting up a specific number of trials, or ii) reaching the proficiency stage (i.e., plateau). By setting a specific number of trials, the participants will be at different points on the performance curve at the end of the task allowing for a comparison of acquisition based on the conditions administered to them. Whereas reaching a plateau stage, it implies that performance remains constant and relatively unchanged based on the sigmoid framework [106]. An informal pilot test was conducted with five undergraduate students from the Game Development and Interactive Media program at Ontario Tech University and showed that the average number of trials the participants took to complete the task had a high variability making it challenging to have specified a number for the trials. Based on this reasoning, the plateau approach was chosen to determine the completion of the task and to allow for the calculation of the speed of acquisition.

3.5.1 Detecting Performance Plateau

To achieve such a plateau state in the serious game, the task was set to complete when the participants managed to drill the predetermined length five consecutive times. To account for systematic errors such as the variability in equipment (i.e., participants' mouse) [107], a two tail confidence interval of 95% was added. Following the 15 cm length that was decided to be the target depth, the acceptable range to be inside the plateau is 15 ± 0.375 cm calculated by multiplying 15 by 2.5%. To illustrate the number of attempts still required to reach a plateau, a box was added to the upper right corner of the serious game scene. The box contained five dashes that indicate that the player must reach the correct length five times. These dashes were converted to a circle once the correct depth was reached and only increased in number if the player managed to drill the correct depth consecutively (Figure 3.10).

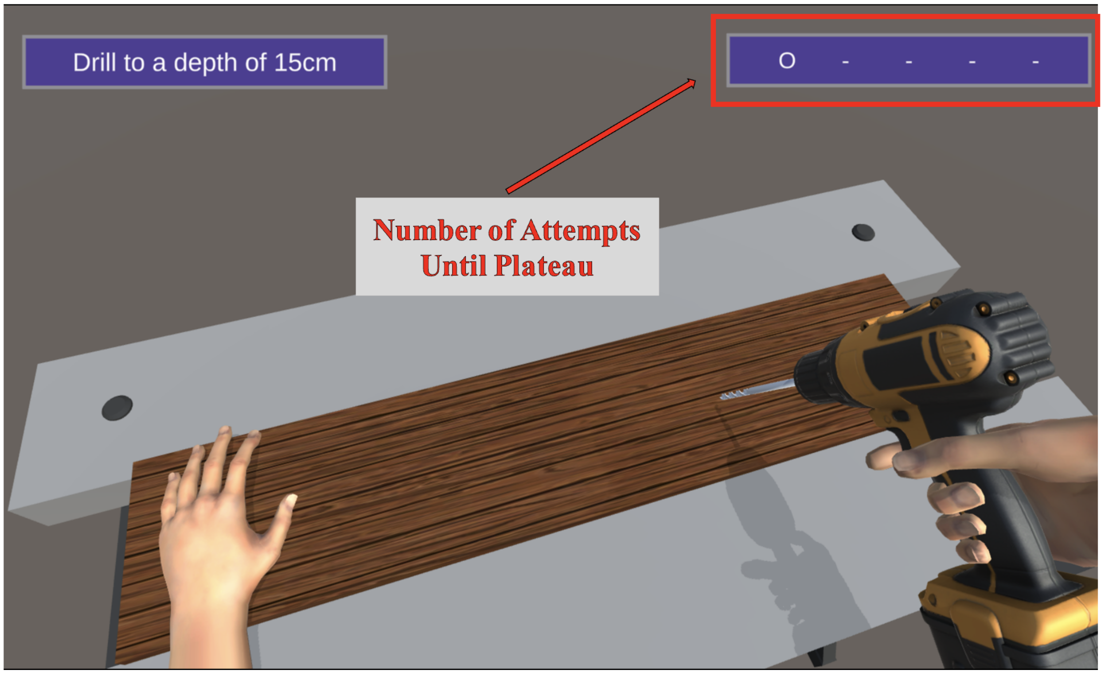


Figure 3.10. Number of attempts to reach plateau counter: The upper right box counts the number of attempts still recruited to reach the plateau. The dash will turn into a circle indicating that the player reached the correct length.

3.5.2 Accounting for Variability Error

Another measure was added to account for variability error when performing the drilling task. To account for human errors that are not related to performing the task, a three "lives" system was added whereby participants could maintain their progress even when they drilled outside the 95% confidence interval (refer to previous section), giving them a bit of 'safety net' for participants. Since the participant's task was to drill to the instructed depth five consecutive times, the "lives" system will not be active, unless the participant completed at least one of the instructed depths accurately (drilled within the 15 ± 0.375 cm range). Once the first depth was accurately performed, the participants had three lives before they were forced to start over. The way deduction of the lives is calculated is based on the Root Mean Square Error (RMSE) [108]. RMSE, or otherwise known as total variability error, measures the overall error from the target by taking the square sum of the observed trial score and the target score difference; the numerator is then divided by the total number of trials followed by taking square root off the total (Equation 3.1).

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(x_i - T)^2}{N}}$$

Equation 3.1. RMSE equation where:
x_i = observed score; T = target score; N= total number of trials

The RMSE score ranges from 0 to 100 and a lower score indicates that the observed values better fit the model. There are discussions on what is considered a good RMSE score and based on the work of Moriasi et al. (2007), it was decided that in this study, only RMSE scores below or equal to 0.5 will be deemed acceptable [109]. When a participant drills outside the acceptable depth of 15 ± 0.375 cm after successfully completing at least once within the allowable drilling range, the RMSE score of the "plateau" values along with the last trial (length outside the acceptable depth) was calculated. If the RMSE score is equal to or lower than 0.5, the participant will lose a 'life' and will be allowed to resume the trials. If the score was greater than 0.5, the previous attempts to "plateau" will be disregarded, and the participant will have to start from one out five plateau attempts once again. To ensure that the participants perform the task as accurately as possible, no visual representation of the number of "lives" was put in place. If the participant was within the 0.5 RMSE score, they were told that they had a ‘second chance’ at performing the task more accurately so that they would not lose their streak (Figure 3.11). It should be noted that no additional ‘plateau’ score will be added to the existing ones unless the participant drills the acceptable range of 15 ± 0.375 cm during one of their three ‘Second Chances’. Once all three ‘lives’ have been used the participant will have to restart from one out five plateau attempts.

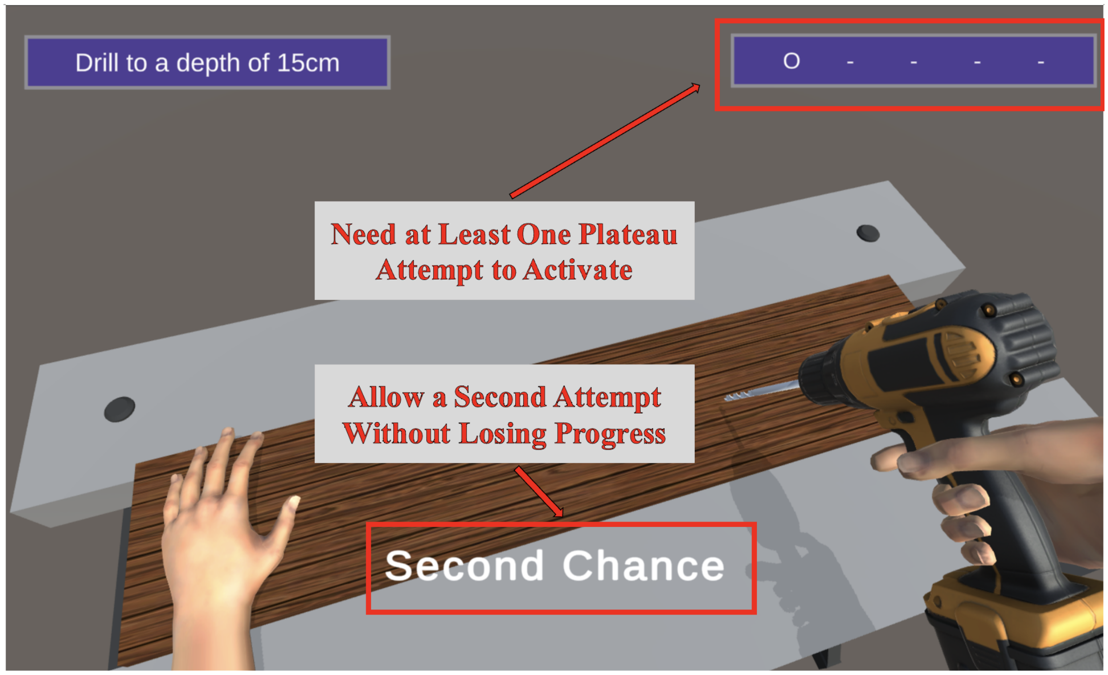
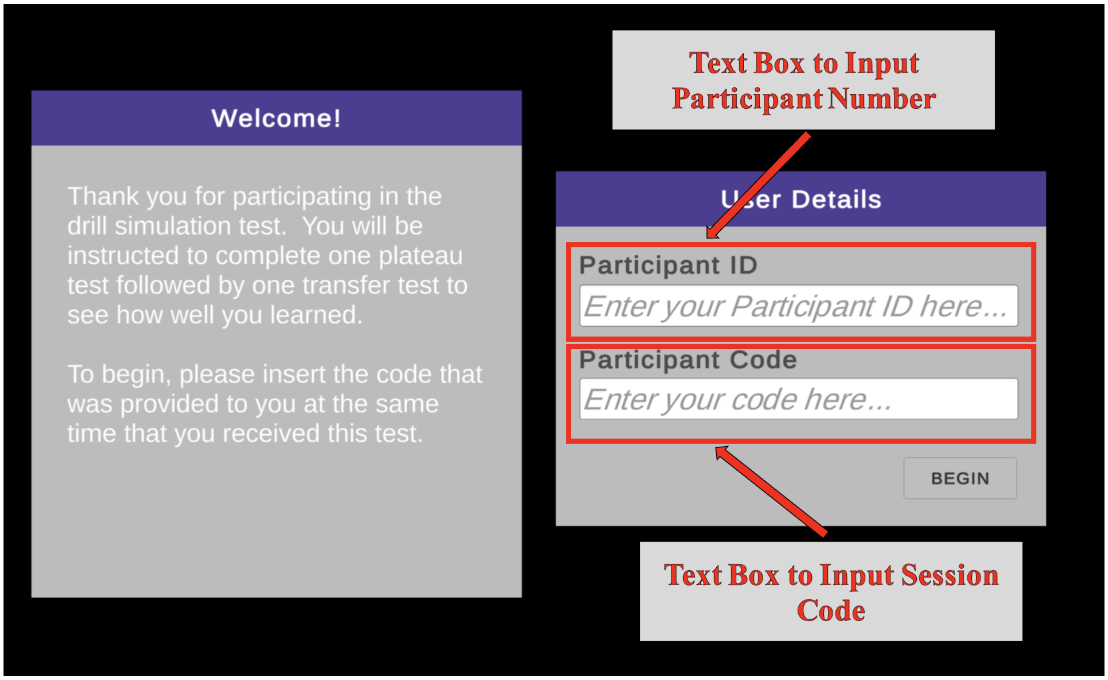


Figure 3.11. ‘Second Chance’ only activates once participants make one plateau attempt successfully and allows the participant to take a second attempt without losing process when drilling outside the acceptable range of 15 ± 0.375 cm.

3.6 Linking Experimental Conditions to Participants

The participants will perform two sessions, i) a practice and ii) a transfer test, as part of the study. To ensure that a practice session is coupled with a transfer test while ensuring the anonymity of the participants, participant numbers were provided to each participant. The participants were asked to enter the participant number assigned to them and the session code (that assign an experimental condition for both the practice and transfer test) before the start of each session (Figure 3.12).



Text Box to Input Participant Number

Welcome!

Thank you for participating in the drill simulation test. You will be instructed to complete one plateau test followed by one transfer test to see how well you learned.

To begin, please insert the code that was provided to you at the same time that you received this test.

User Details

Participant ID

Enter your Participant ID here...

Participant Code

Enter your code here...

Text Box to Input Session Code

Figure 3.12. Participant and session information: Before the start of the session, participants are asked to input their participant number and special code unique to the session containing the predetermined condition.

Chapter 4. Methods

4.1 Overview

This chapter will discuss the preliminary study that will enable the answering of the research question and three objectives, i.e., to determine if embodiment is possible using 2D equipment, and if the use of embodiment coupled with pseudo-haptics enhanced the speed of acquisition and learning of the drilling task. The chapter will end by outlining quantitative dependent variables and qualitative elements of interest that were collected in the study.

4.2 Experimental Design

This thesis work consisted of a preliminary study whose purpose was to determine whether the addition of a virtual hand to the drill (change in visual condition) enhances speed of acquisition, learning, and embodiment. To accomplish the task, we coupled an auditory condition against our visual stimuli, a hand holding the drill, in the presence of a haptic stimuli.

4.2.1 Visual Stimuli

Two visual conditions were tested to answer the research question and acted as independent variables for the study. One of these visual conditions utilized is a hand holding the virtual drill, which represents embodiment (Figure 4.1).

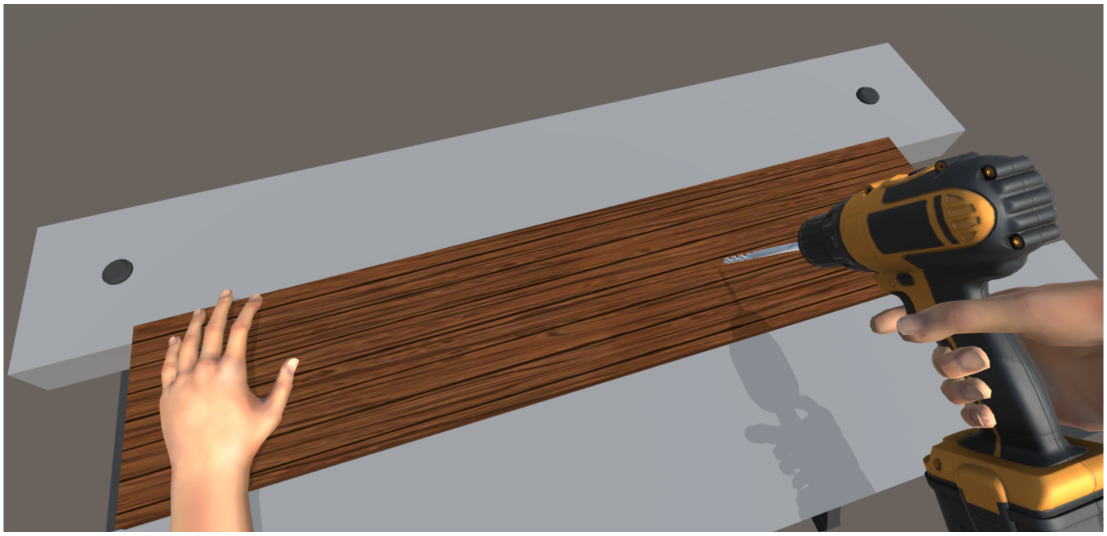


Figure 4.1. Visual Stimuli showing the virtual hand holding drill in front of the block of wood.

The second visual condition consisted of a visual drill in front of the block of wood that the participant will be drilling into without the hand (Figure 4.2). This visual condition represents non-embodiment.

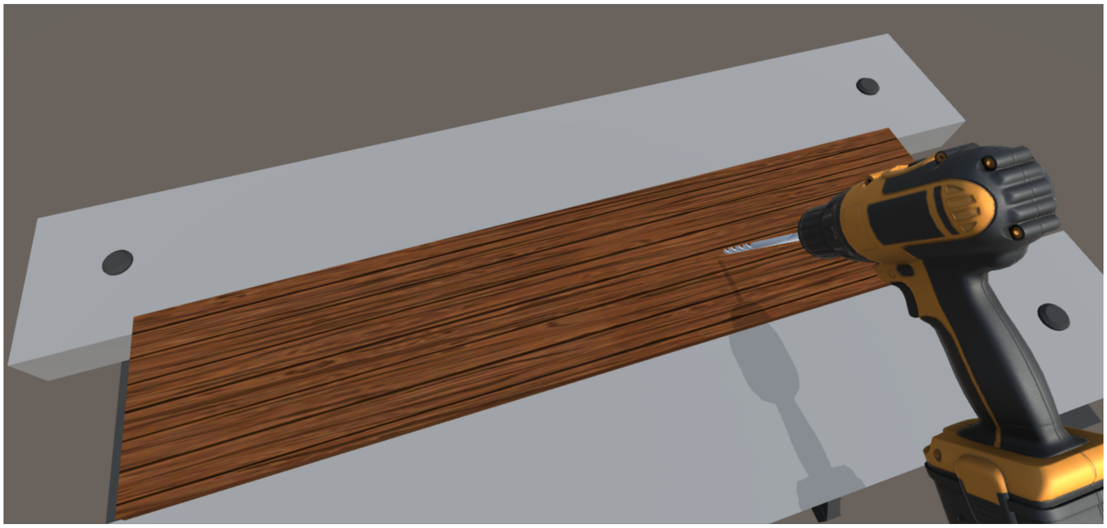


Figure 4.2. Visual Stimuli showing the virtual drill in front of the block of wood that the participants will be drilling.

4.2.2 Auditory Stimulus

Since embodiment requires a multi-modal interaction, the visual stimuli will be coupled with a control auditory stimulus. One of the three sound conditions used by Ning et al. (2023) in his study (discussed in the previous chapter) was used. This sound condition is contextual sound, which portrays a dynamic sound feedback whose pitch changes depending on the depth to notify the participants about the change in depth (e.g., the sound is related to the drilling task).

4.2.3 Haptic Stimulus

Since embodiment requires a multi-modal interaction, a haptic component is necessary to elicit the experience and will be coupled with both the visual and auditory stimuli. Similar to the auditory stimulus, Ning et al. (2023) also used kinesthetic feedback in his study. Kinesthetic feedback was achieved using the mouse to allow the participants to feel a “force” when using the mouse to move the drill into the virtual piece of wood. More specifically, kinesthetic feedback was elicited by grasping and manipulating the participants’ computer mouse, which provided the participant information on the virtual drill position and movement in the virtual simulation without the use of a haptic device.

Moreover, the participants’ computer mouse was also used to control the drill. The left button on the mouse activates the drill, moving the mouse forward and backwards will move it toward and away from the block of wood, and releasing the left button will deactivate the drill and reset it to its original location.

4.3 Participants

Recruitment emails (refer to Appendix B1) were originally sent out to Ontario Tech University students from an email list provided by my supervisors. However, due to the small number of students during the summer semester, not enough responses were received, and a broader search was necessary to ensure the number of participants required for the study. Once the REB amendment was approved for external recruitment, the snowballing sampling technique was used to recruit the remaining participants recruited for the study.

Upon participants expressing interest, a follow-up email was sent to inquire about the participant's availability to schedule the practice and transfer test session. Participants were required to be available two days in a row to account for the 24 hours practice to transfer test time. Once a preferred time was agreed upon, two Google Meets invitations were sent out and a follow-up email containing the consent form (refer to Appendix B2) was sent to the participants.

On the day of the experiment, the experimenter (myself) made sure that the participants understood all sections of the consent form and answered any question they might have before asking them to sign the consent form. Once the consent form was signed, an executable file was sent to the participants, who were instructed to download it onto their computers. The experimenter asked the participants to share their screen once the serious game was downloaded successfully onto the participants' computers and introduced the serious game and explained to them how to control the drill and what their task includes. The experimenter ensured that the participants were using a computer mouse and headphones, and remained on the call during the entirety of the session to facilitate and answer any questions that may have arisen.

In total, 43 participants voluntarily took part in the study. Three of the participants' data had to be removed for the following reasons: i) one of the participants dropped out after the first session; ii) one participant had technical difficulties while performing the drilling task causing the discrepancy in the results; iii) one participant's results fell three standard deviations away from the mean and was considered an outlier. All three participants who were removed were in the embodiment experimental group, totaling 23 participants in the embodiment group and 20 participants in the non-embodiment group. With the three participants removed, 40 participants remained which were equally divided (20) amongst the two experimental groups.

From the remaining 40 participants, 32 of them were Ontario Tech University students between the ages of 18 to over 30 years of age and the remaining eight were recruited from outside of the institution and are between the ages of 18 and 30. Based on the requirements to participate, all participants had experience using a drill and reported normal hearing (i.e., no hearing problems). No compensation was provided to participants for their participation (i.e., they had the right to withdraw from the study at any time during and after the completion of the sessions).

4.4 Procedure

The study was conducted live in front of the experimenter via Google Meet and ran for approximately 20 minutes. Visual conditions: i) embodiment, through the representation of the virtual hand holding the drill, and ii) non-embodiment, through the representation of just the drill were assigned randomly to the participants. Both groups regardless of the condition assigned included contextual sound as the auditory stimulus and the pseudo-haptics kinesthetic feedback as the haptic stimulus (Table 4.1).

Table 4.1: The multi-sensory conditions employed in this study.

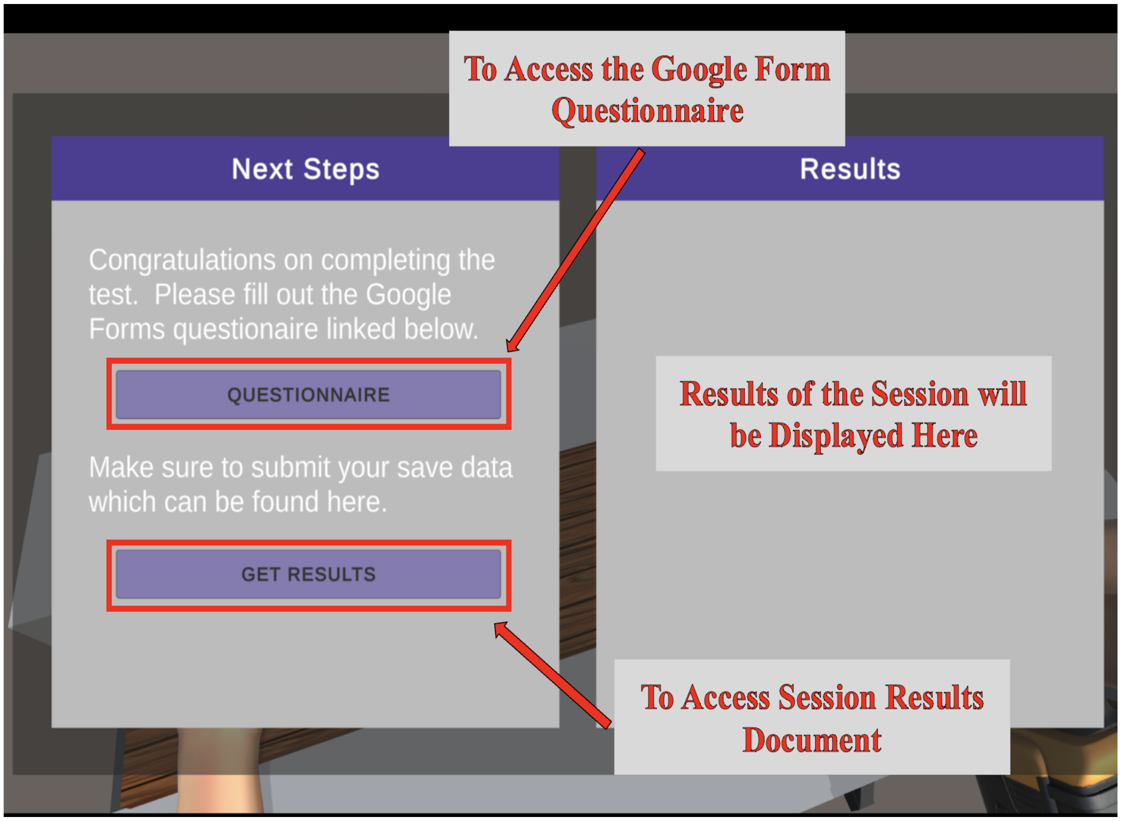
		Sound conditions **&** **Haptic condition**
		Contextual & Kinesthetic feedback
Visual conditions	*Embodiment* (Drill and Hand)	
	Non-Embodiment (Just Drill)	

Participants were asked to perform a drilling task from a first-person perspective, and the study was composed of two consecutive sessions: i) a practice session, followed by ii) a transfer test. Instructions are given at the beginning of each session outlining the task.

4.4.1 Practice Session

At the start of the experiment, the participants were asked to take part in a training session to familiarize themselves with the process (i.e., the drilling simulation). Their task was to drill 15 cm through a virtual piece of wood, under the two visual conditions (embodiment or non-embodiment) randomly assigned to the participants prior to the start of the session, contextual as the sound condition and kinesthetic feedback as the haptic condition were present in both groups. Participants were locked into the practice session repeating the drilling exercise until they plateaued, which consisted of drilling within a 95% confidence interval of the requested depth five times consecutively. Once the participants succeeded in performing the task, they were asked to return after 24 hours to complete the transfer test part of the study.

At the end of the practice session, the participants were led to ‘Next Steps’ page where the participants was able to access the Google Form containing the two questionnaires administered using: i) the Embodiment Questionnaire that measures participants’ perceived embodiment [48] and ii) Game Engagement Questionnaire (GEQ) that measures their engagement in the virtual environment [110]. This page also portrayed the results of the practice and allowed the participants to retrieve the text-formatted file containing the results (Figure 4.3). Participants' task completion time and the number of trials it took them to complete the practice were also recorded. Moreover, participants were asked to provide their feedback and comments at the end of the questionnaire; these responses were used as qualitative data.



Congratulations on completing the test. Please fill out the Google Forms questionaire linked below.

Make sure to submit your save data which can be found here.

Figure 4.3. 'Next Steps' page: At the end of each session, this page allows the participants to access their results and the Google Form containing the questionnaires.

4.4.2 Transfer Session

To ensure that the participant's performance was due to the conditions being studied and not repetition, they were asked to perform a cross-over transfer test using the conditions of the practice session.

Each of the 20 participants that took part in the practice session was once again equally divided into two groups with 10 participant each and randomly assigned one of the two visual conditions: i) embodiment with contextual sound and kinesthetic feedback and ii) non-embodiment with contextual sound and kinesthetic feedback (Figure 4.4). This assignment was pre-determined prior to the start of the experiment to avoid error and to save time. The participants were provided with a code to enter the transfer test condition that has been assigned to them. Their task was to drill 9 cm into the piece of wood **once**.

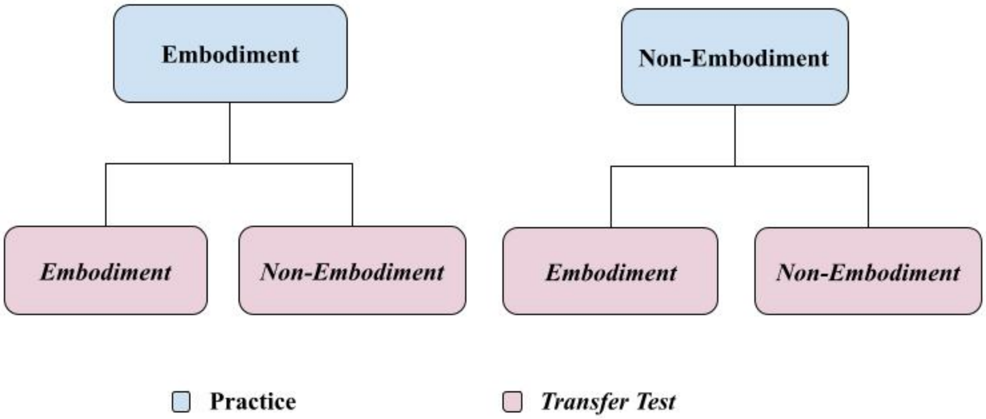


Figure 4.4. Flowchart portraying experimental conditions in the practice and transfer test sessions.

After the end of each session (both practice and transfer), the participants were asked to upload the results of the session on a Google Form and send it back to the experimenter (Refer to Figure 4.3 for information on how to access the questionnaire and results).

4.5 Dependent Variables

The following two sections discuss the different quantitative variables employed, followed by the qualitative elements of interest. The sections will also outline the different analysis methods used for each data type. This research study employed an Embedded Mixed Design method [111] where both quantitative and quantitative data were collected simultaneously and quantitative data acted as the main type of data.

Quantitative responses were embedded to provide a supporting role in answering the research question.

4.5.1 Quantitative Variables

Different measures were collected from the participants during the practice and transfer test sections. These statistics include: i) the number of trials the participant took to complete the study; ii) the total time the participant took to complete the study; iii) transfer test drilling depth; iv) the Embodiment Questionnaire (refer to Appendix C2) scores; v) the GEQ (refer to Appendix C3) scores. These analyses were conducted using R. Excel was used to generate graphs and diagrams portrayed in the result section. The Shapiro-Wilk normality test was conducted on all the variables to determine which test is the most appropriate to use. Those whose p-values were higher than 0.05 ($p \geqslant 0.05$) based on the Shapiro-Wilk test were deemed having a normal distribution and those with a p-value less than 0.05 ($p \leqslant 0.05$) were deemed to not have a normal distribution. Normally distributed variables were tested using a t-test for two sample variables and two-way ANOVA for those with more than two variables. The Mann-Whitney U test was conducted for variables deemed to not have a normal distribution. A size effect test was conducted on statistically significant variables to determine how strong the relationship between the two variables.

4.5.1.1 Total Completion Time

A one-tail two-sample t-test assuming equal variance was conducted to compare the overall time that the participants took to complete the drilling task in each group (embodiment vs. non-embodiment). Time (s) was recorded as soon as the participants pressed ‘begin’ and stopped when they completed their final drill successfully. The total time was then divided by 60 to obtain the time in minutes for clarity and ease of comprehension. An alpha value of 0.05 was chosen to determine results significance.

4.5.1.2 Number of Attempts

A Mann–Whitney U test was conducted to compare the overall number of attempts between experimental groups (embodiment vs. non-embodiment). First, A two-tailed Mann–Whitney U test was first conducted to ensure significance, then a one-tailed Mann–Whitney U test was performed to test the hypothesis: The embodiment group will make fewer attempts to complete the drilling task than the non-embodiment group. The number of attempts portrays the number of drilling trials that the participant performed to complete the task. An alpha value of 0.05 was chosen to determine results’ significance.

4.5.1.3 Transfer Test

On Day 2 of the study, 24-hours after the practice session, the participants were asked to take part in a transfer test where they had to drill to a 9 cm depth one time. The participants were once again randomly assigned to a condition (embodiment vs. non-embodiment), leading to four groups in total: i) Embodiment/Embodiment (E/E); ii) Embodiment/Non-Embodiment (E/NE); iii) Non-Embodiment/Embodiment (NE/E); iv) Non-Embodiment/Non-Embodiment (NE/NE).

A two-way ANOVA was conducted to compare the drilling depth error (depth drilled - actual depth of 9 cm) between the two transfer test conditions (embodiment vs.

non-embodiment) split on the two practice factors (Table 4.2). An alpha value of 0.05 was chosen to determine results significance.

Table 4.2: Transfer test's drilling depth error conditions.

		Transfer test	
		Embodiment	Non-Embodiment
Practice	Embodiment	E/E	E/NE
	Non-Embodiment	NE/E	NE/NE

4.5.1.4 Creating the Survey

At the end of the practice session on Day 1 of the study, the participants were asked to complete two questionnaires: i) the Embodiment Questionnaire [48]; ii) the Game Engagement Questionnaire (GEQ) [110], two valid and reliable questionnaires. To provide the participants privacy while completing the questionnaires, they were asked to stop sharing their screen and let the experimenter know when they submitted their responses. This was done to ensure that the participants were not pressured to answer a certain way just because the experimenter was watching at screens. The experimenter remained on the Google Meet call to answer any questions the participants had while completing the questionnaires. In this section of the chapter, the results of these questionnaires will be portrayed.

Google Form was used to construct the survey due to its accessibility, ease of use and anonymity. The first page of the questionnaire contained drop boxes where participants could upload their consent form and experiment results. It also included broad questions such as asking for participants number and participants age range (Refer to Appendix C1).

The second page consisted of the Embodiment Questionnaire where participants rated their perceived embodiment on a 7-point Likert scale from (1) being strongly disagree to (7) being strongly agree. Peck and Gonzalez-Franco (2021)'s Embodiment questionnaire allows the examiner to edit the questions to personalize it based on their study. These edits include specifying body parts that are being studied and what is that body interacting with [48]. To avoid any confusion since the virtual hand is what is being manipulated, two versions of the questionnaires were created and administered depending on the experimental condition (Refer to Appendix C2). The third and final page of the questionnaire consisted of the GEQ, developed by [110], where the participants rated their engagement in the serious game on a three-point Likert scale (No; Maybe; Yes) (Refer to Appendix C3).

4.5.1.4.1 Game Engagement Questionnaire

The GEQ, developed by [110], consists of four subcomponents that were first computed then averaged to provide the total game engagement. These four subcomponents are: i) immersion; ii) presence; iii) flow; iv) absorption. Although some of these terms are usually misused, as previously mentioned, immersion is the state of being engaged in an experience while keeping conscious awareness of one's surroundings and presence is the state of consciously being inside a virtual environment [110]. Flow is the balance between the feeling of accomplishing a rewarding task and the skill being performed. Immersion and setting goals enhance the state of flow [110]. Whereas absorption is an altered state of consciousness of being totally engaged in an experience.

To calculate total engagement, participant responses for each of the four subcomponents, and the participants' combined subcomponent responses were standardized to provide a condition engagement score. A one-tail two-sample t-test assuming equal variance was conducted to compare the overall engagement between the two groups (embodiment vs. non-embodiment). An alpha value of 0.05 was chosen to determine results significance.

4.5.1.4.2 Embodiment Questionnaire

The embodiment questionnaire, developed by [48], consists of four subcomponents that were used to compute the total embodiment. The subcomponents include: i) appearance, ii) response, iii) ownership, iv) multi-sensory. Although self-location and agency are also included in the questionnaire, they are part of the four subcomponents and were calculated as such [48]. To calculate the level of embodiment in each group, participant responses for each of the four subcomponents were first calculated, and then these combined subcomponent responses were standardized to provide a total embodiment score.

A one-tail two-sample t-test assuming equal variance was conducted to compare the overall embodiment between the two groups (embodiment vs. non-embodiment). An alpha value of 0.05 was chosen to determine results significance.

4.5.2 Qualitative Elements of Interest

A statement on the embodiment questionnaire used a 7-point Likert scale to answer the following: ***I felt a sensation in my body when I saw the virtual hand*** for the *embodiment* group, and ***I felt a sensation in my body when I saw the virtual drill*** for the *non-embodiment* group. Both were followed by a short-answer question asking: ***If you felt a sensation in your body when you saw the virtual [hand for the embodiment group and drill for the non-embodiment group], what sensation did you feel?*** The responses recorded for this question were analysed as qualitative data using thematic analysis method [112].

Moreover, at the end of the questionnaire, the participants were provided the opportunity, if they wished, to provide their comments and feedback regarding their experience (Refer to Appendix C4). These results were recorded and analysed as qualitative data to support the quantitative data. A thematic analysis method was chosen over other qualitative analysis methods because these open-ended questions aimed to collect information on participants' views, opinions, and experiences, in which thematic analysis method allows the most flexibility in finding the common themes [113].

4.6.2.1 Thematic Analysis Method

Thematic analysis is a popular qualitative analysis method that identifies patterns in raw data and organizes them in themes [112]. This method consists of an eight-step process: i) Familiarization; ii) Coding; iii) Codebook; iv) Theme Development; v) Theorizing; vi) Comparison; vii) Displaying the Results and viii) Documenting the Results.

i. **Familiarization** is the first step of the thematic analysis approach and consists of going through the raw data by actively reading and taking notes of areas of interest.
ii. The **Coding** stage categorizes the raw data into a word or phrase that best symbolizes it. Multiple rounds of the code stage are recommended to effectively group the data. The first round of code establishes a link between the data and an interpretation of this data. Every sentence and/or paragraph was provided with a code. The second round of code is more selective and looks at the 'codes' provided in round one and groups phrases and paragraphs of the same code under one heading to establish a deeper level of meaning.
iii. The **Codebook** stage ensures that the coding process is performed correctly by providing its verification. The way the codebook stage was conducted in this thesis work is by getting a second opinion on the grouped data. An excel sheet containing anonymous participants' comments and feedback was sent to a PhD student in the lab who has experience conducting qualitative research and was asked to code the responses. The codes were then compared, and a third round of code was conducted to finalize the categories.
iv. **Theme development** is an important aspect of the data. Themes are established by examining the relationship between the codes and how they relate to one another.
v. The **theorizing** stage explains the relation between the themes and the data and how the themes relate to the study and fit topic being examined.
vi. The **comparison** stage, although optional, examines whether or not qualitative results supported quantitative data results.

vii. The results of the **data** will be **displayed** visually in a form of a flow chart outlining the overarching themes, codes, and the direct quotes from participants' responses. The flow charts were created using Google Drawing tool.

viii. **Documentation** of the results are presented in sections 5.6.1 and 5.7 of the results chapter.

Chapter 5. Results

5.1 Overview

The following chapter will outline the results of the previously described experiment. The quantitative variables collected were: i) drilling task completion time, ii) total number of attempts taken to complete the task, iii) the results of the embodiment and iv) engagement questionnaires, and v) the results of the transfer test. The chapter will end with the qualitative results of the open-ended question.

5.2 Total Completion Time

The results of the Shapiro-Wilk normality test indicated a normal distribution in the total completion time data (W = 0.947, p = 0.0591). General statistics of total completion time (mins) showing the number of participants, mean, standard deviation, standard error and variance in each sample group is presented in Table 5.1.

Table 5.1: Total completion time's (mins) general statistics.

	n	**Mean**	**Std. Deviation**	**Std. error**	**Variance**
Embodiment	20	9.021	5.673	1.269	32.186
Non-Embodiment	20	13.202	5.394	1.206	29.096

The results indicate that there was a statistically significant difference between the time that the embodiment group took to complete the task in comparison to the non-embodiment group (t (38) = -2.389, p = 0.011). Based on these results, the null hypothesis was rejected indicating that the embodiment group took significantly less time to reach proficiency and thus has a greater speed of acquisition than the non-embodiment group (Figure 5.1). This effect between embodiment and non-embodiment time to completion is moderate according to Cohen's d test (d = -0.755). Thus, coupling embodiment with pseudo-haptics moderately improves the speed of drilling task acquisition.

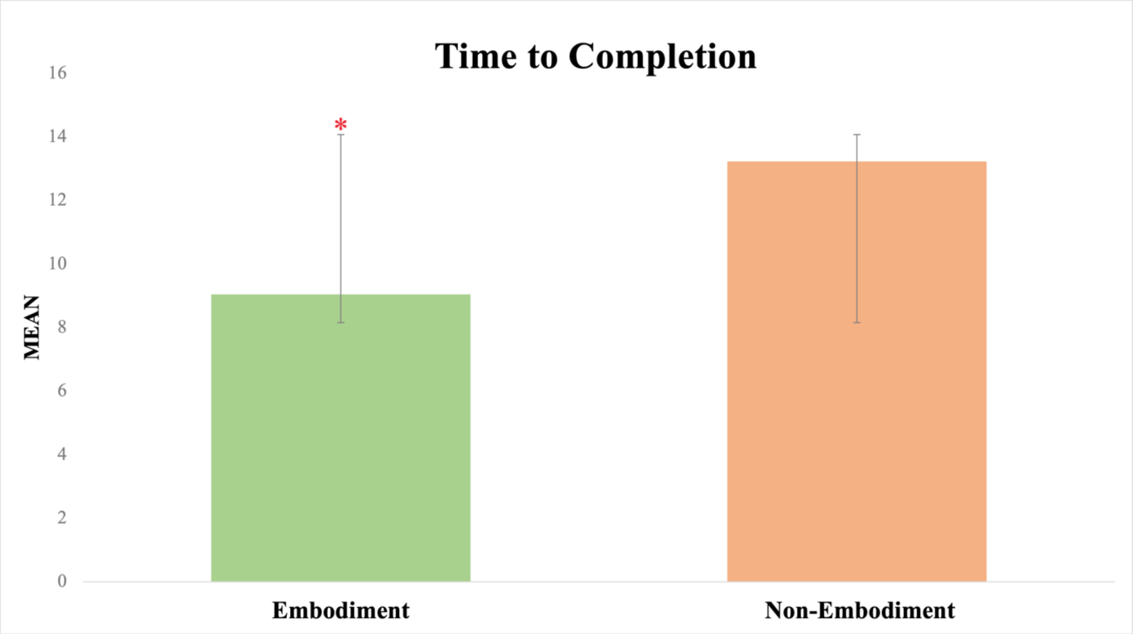


Figure 5.1. Average time to completion (min) between the Embodiment vs. Non-Embodiment groups. The whisker shows standard deviation and the '*' shows significance ($p \leqslant 0.05$).

5.3 Number of Attempts

The Shapiro-Wilk normality test revealed that the number of attempted data is not normality distributed (W = 0.861, p = 0.0002). General statistics of the total number of attempts showing the number of participants, mean, standard deviation, standard error and variance in each sample group is provided in Table 5.2.

Table 5.2: Number of attempts' general statistics.

	n	Mean	Std. Deviation	Std. error	Variance
Embodiment	20	51.2	47.332	10.584	2240.274
Non-Embodiment	20	72.75	49.627	11.097	2462.829

The results of the Mann–Whitney U test indicate significance in the number of attempts between both groups (U = 127.5, p = 0.050 for two-tailed; p = 0.025 for one-tail). The null hypothesis is rejected, indicating that the embodiment group significantly took a smaller number of attempts to reach proficiency thus has a greater speed of acquisition than the non-embodiment group. Hence, embodiment coupled with pseudo-haptics does change performance measured using the number of attempts. (Figure 5.2). This effect between embodiment vs. non-embodiment with respect to the number of attempts is moderate (r = -0.363), according to the Mann-Whitney-U-Test Effect Size. Hence, there is a moderate increase in speed of acquisition between the two groups when considering the number of attempts it took for participants to complete the task.

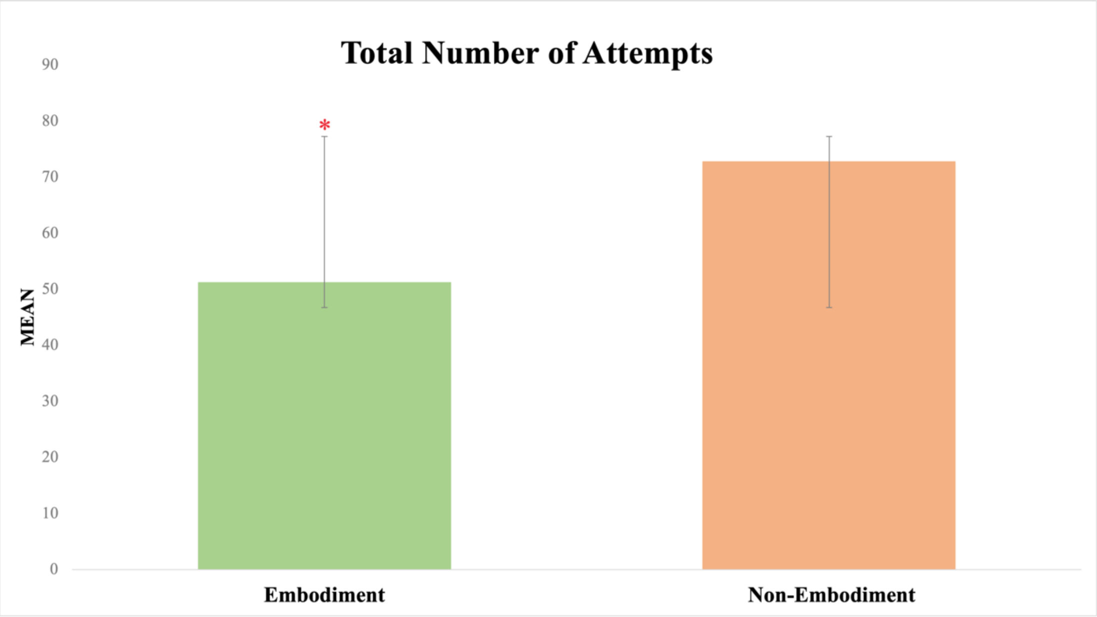


Figure 5.2. Average number of attempts between the Embodiment vs. Non-Embodiment groups. The whisker shows standard deviation and the '*' shows significance ($p \leqslant 0.05$).

5.4 Transfer Test

The results of the Shapiro-Wilk normality test indicated a normal distribution in the total completion time data ($W = 0.976$, $p = 0.532$). General statistics of the transfer test's depth error showing the number of participants, mean, standard deviation, standard error and variance in each sample group is provided in Table 5.3.

Table 5.3: Transfer test's depth error's general statistics.

	n	Mean	Std. Deviation	Std. error	Variance
E/E	10	0.411	1.329	0.420	1.766
E/NE	10	0.520	1.898	0.600	3.604
NE/E	10	-0.741	1.481	0.468	2.193
NE/NE	10	0.510	2.534	0.801	6.415

Based on the results, although the E/E average drilling depth error is closest to the 9 cm target, this difference is not statistically significant as there is no statistical significance between practice conditions and transfer test conditions (F (1, 36) = 0.933, p = 0.341), regardless the practice condition. Moreover, simple main effects analysis showed no statistical significance between transfer test conditions and transfer test's depth error (p = 0.258) and between practice conditions and transfer test's depth error (p = 0.332). Moreover, there was no significant difference between the interaction of practice conditions and transfer conditions (p = 0.341). The null hypothesis is not rejected, indicating that there is no difference in transfer test results between the four groups, hence all groups learnt the drilling task similarly (Figure 5.3). Coupling embodiment and pseudo-haptics does not seem to affect learning of the drilling task.

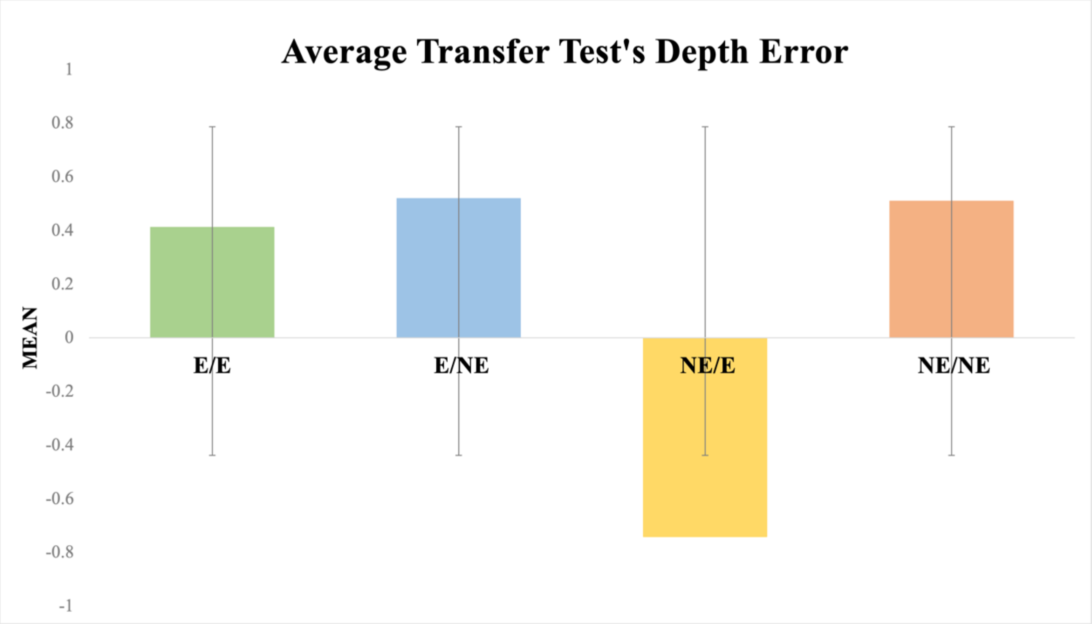


Figure 5.3. Average depth error (depth drilled - target depth) of Transfer test (cm) between the four groups. A mean of '0' represents the target depth (9 cm), positive means indicates an overshoot, whereas negative represents undershoot. The whisker shows standard deviation.

5.5 GEQ

The results of the Shapiro-Wilk normality test indicated a normal distribution in the total completion time data (W = 0.984, p = 0.834). General statistics for total engagement showing the number of participants, mean, standard deviation, standard error and variance in each sample group is provided in Table 5.4.

Table 5.4: Total engagement score's general statistics.

	n	**Mean**	**Std. Deviation**	**Std. error**	**Variance**
Embodiment	20	2.064	0.350	0.078	0.122
Non-Embodiment	20	2.081	0.388	0.087	0.151

The results show no statistical significance between the embodiment and non-embodiment groups (t (38) = 0.141, p = 0.444). Interestingly, the average level of presence and absorption were slightly higher in the embodiment group, yet average immersion and flow were slightly higher in the non-embodiment group. However, none of the four subcomponents of the GEQ were significantly different either, indicating no difference in engagement between embodiment and non-embodiment groups (Figure 5.4). The lack of significant difference indicates that both groups were equally engaged in the drilling task simulation, regardless of embodiment.

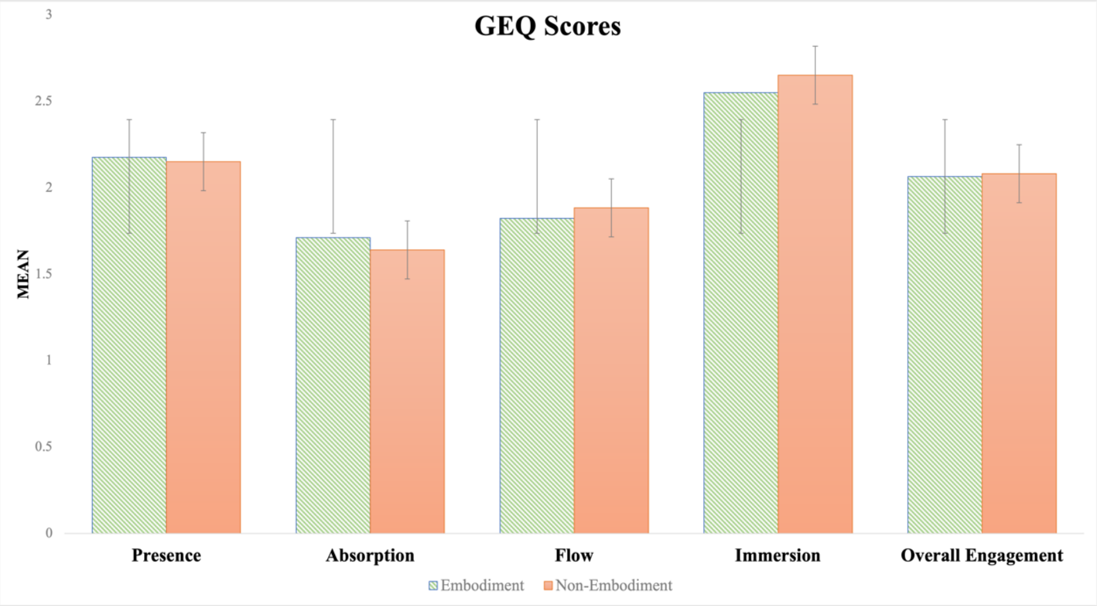


Figure 5.4. Average GEQ scores showing the four subcomponents and overall engagement between embodiment and non-embodiment groups. The whisker shows standard deviation.

5.6 Embodiment Questionnaire

The results of the Shapiro-Wilk normality test indicated a normal distribution in the total completion time data (W = 0.985, p = 0.861). General statistics for total embodiment score showing the number of participants, mean, standard deviation, standard error and variance in each sample group is provided in Table 5.5.

Table 5.5: Total embodiment score's general statistics.

	n	Mean	Std. Deviation	Std. error	Variance
Embodiment	20	3.650	1.276	0.285	1.628
Non-Embodiment	20	3.898	1.114	0.249	1.240

Interestingly, the results of the questionnaire showed lower mean values for the embodiment group (those with the hand holding the drill) than the non-embodiment group. However, these differences were not significant, indicating that there was no difference in perceived embodiment between the two groups (t (38) = 0.653, p = 0.258). Hence, the addition of the hand did not enhance the sense of embodiment (Figure 5.5).

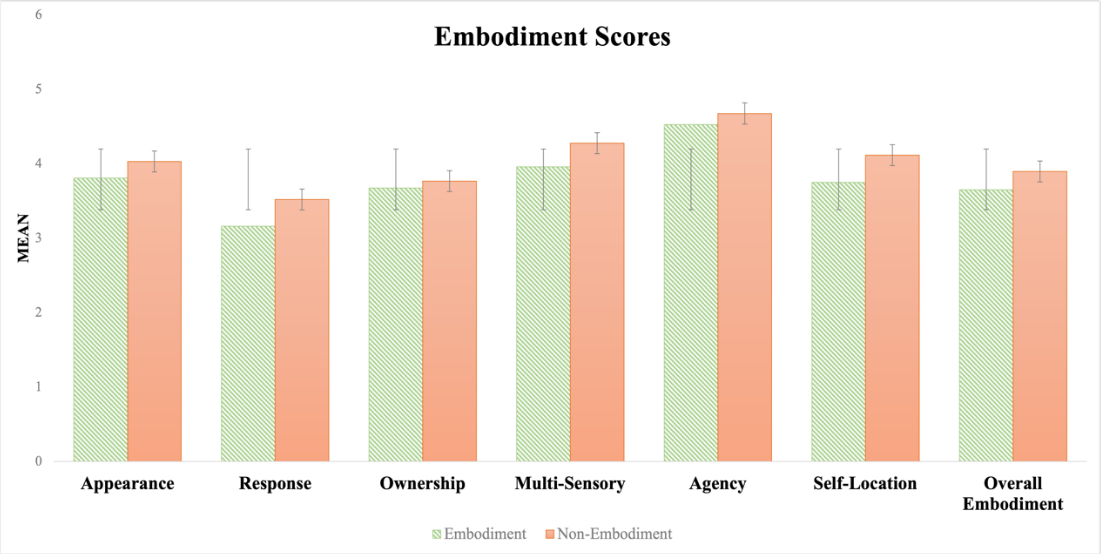


Figure 5.5. Average Embodiment scores between the two groups: the four subcomponents, agency, self-location, and total embodiment between two groups, ‘embodiment’ (hand holding the drill) vs. ‘non-embodiment’ (no hand holding the drill) are portrayed. The whisker shows standard deviation.

5.6.1 Embodiment Questionnaire: Qualitative Results

One of the questions in the embodiment questionnaire asked the participant what sensation they felt inside their body while performing the drilling task. The open-ended responses were recorded and analyzed using the thematic approach. Two main overarching sensations dominated the responses: i) a neurological sensation in the form of tingling sensation; ii) a muscular sensation in the form of force response.

Out of the 40 participants, seven from the embodiment group and 10 from the non-embodiment group responded to the question. However, some participants may have misinterpreted the question as they provided responses such as ‘excitement’ or ‘curiosity,’ and therefore, these responses were moved to general comments and feedback that will be discussed in a later section (refer to Section 5.7).

After moving these misinterpreted responses, five responses remained in the embodiment group and five in the non-embodiment group. Interestingly, participants in the embodiment group experienced more of the neurological responses such as a tingling or shaky sensation, with the tingling sensation being more dominant, whereas participants in the non-embodiment group experienced more of a muscular response such as force or tension (Table 5.6).

Table 5.6: Responses to sensation felt while performing the drilling task. The numbers represent the frequency of participants’ responses.

	Themes			
	Neurological		**Muscular**	
Frequency in Each Group	**Tingling**	**Shakiness**	**Force**	**Tension**
Embodiment	3	1	1	0
Non-Embodiment	1	0	2	2

5.7 Qualitative Results

Participants' responses to the feedback/comment section were recorded and analyzed using a thematic analysis approach [112]. After ensuring no redundancy between the misinterpreted responses moved from the embodiment questionnaire (the sensation question) and those of the participants' general comments, 12 responses were recorded from the embodiment group and 10 from the non-embodiment group. Five overarching themes were found: i) multi-sensory; ii) identified emotions; iii) hyper-focus; iv) expectations; v) equipment limitation. Each of these themes were further divided into subthemes to best illustrate the responses and their implication. It should be noted that some of the participants' responses fell into more than one subtheme.

5.7.1 Multi-Sensory

The multi-sensory theme examines the sensory queues that participants noticed and/or used to accomplish the task. This theme was broken down into three subthemes: i) auditory; ii) visual, and iii) haptic (Figure 5.6). Interestingly, all the responses of multi-sensory themes are from the embodiment group as no participant in the non-embodiment group mentioned any sensory queues or any 'tricks' they used to complete the task. Most participants' responses seem to rely on visual cues to complete the task.

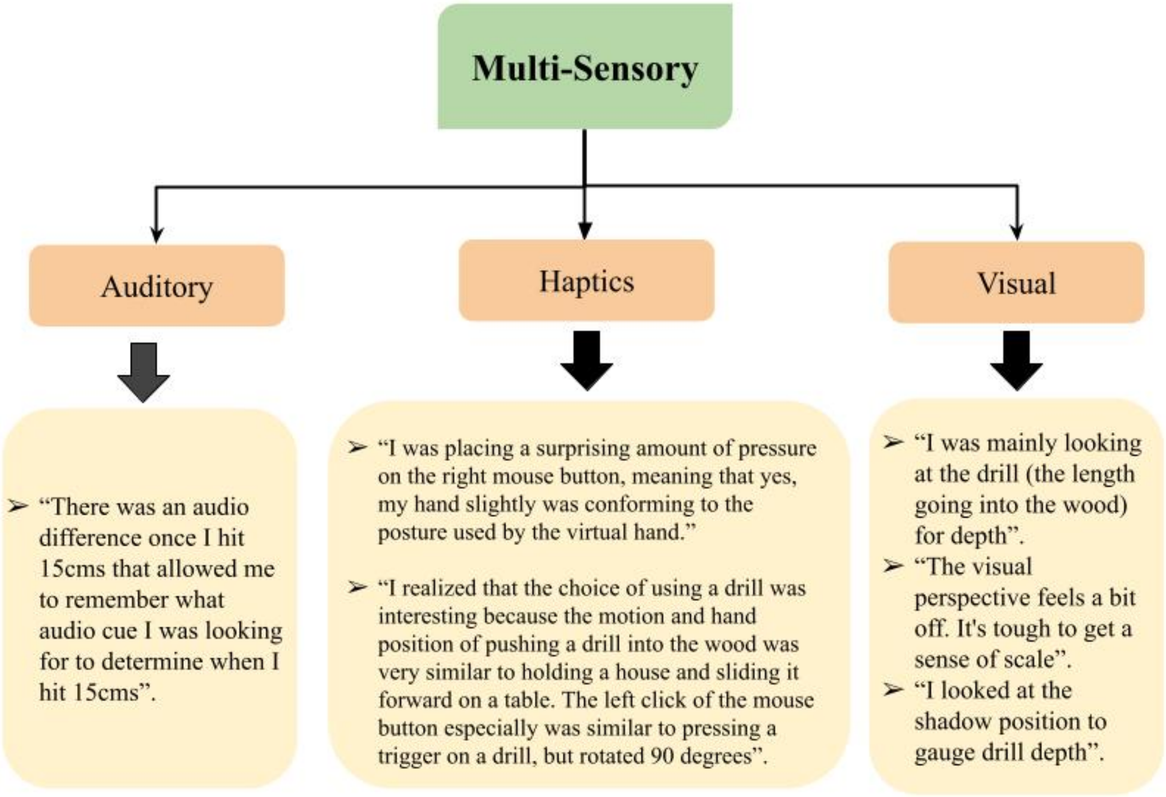
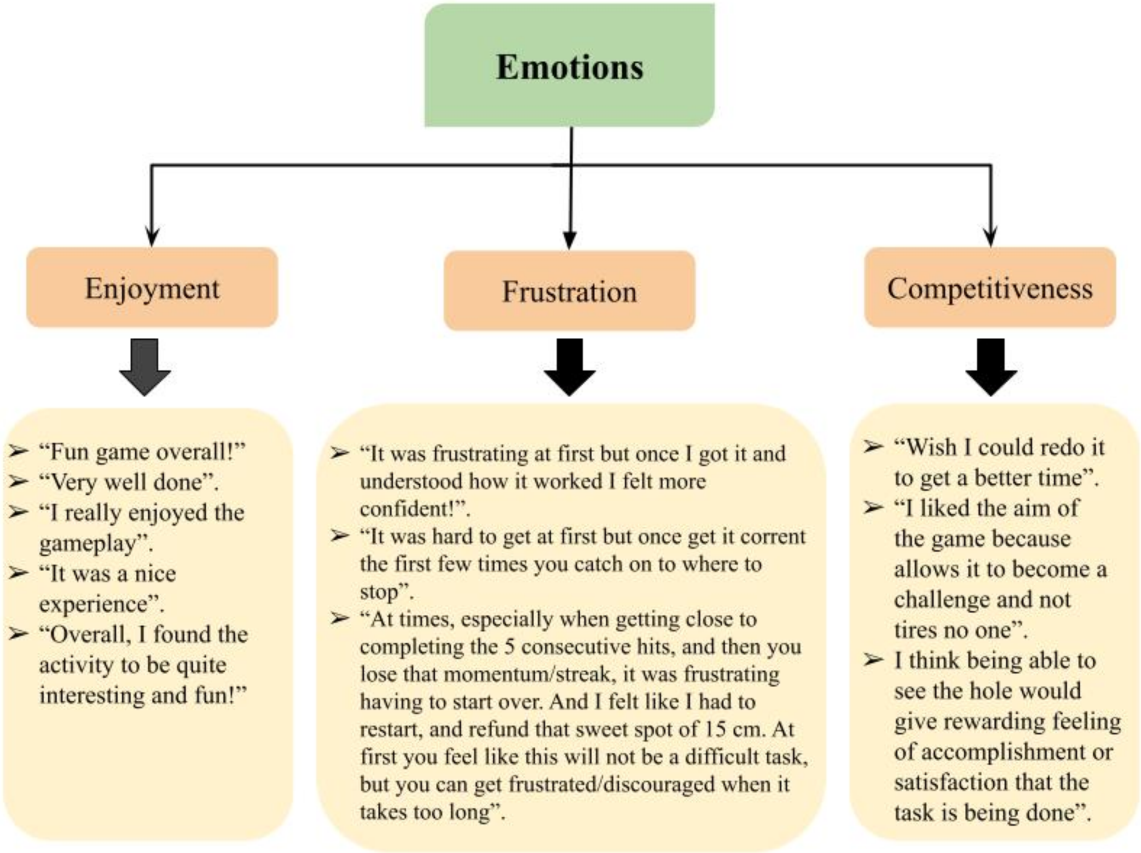


Figure 5.6. A flowchart outlining participants' responses to multi-sensory themes and its subthemes.

5.7.2 Identified Emotions

The identified emotion's theme includes all the different emotions outlined by participants' responses. These emotions include: i) enjoyment; ii) frustration and iii) competitiveness (Figure 5.7). The responses to this theme were seen in both the embodiment and non-embodiment group, yet were more prominent in the non-embodiment group, especially those of frustration and competitiveness.



- “Fun game overall!”
- “Very well done”.
- “I really enjoyed the gameplay”.
- “It was a nice experience”.
- “Overall, I found the activity to be quite interesting and fun!”

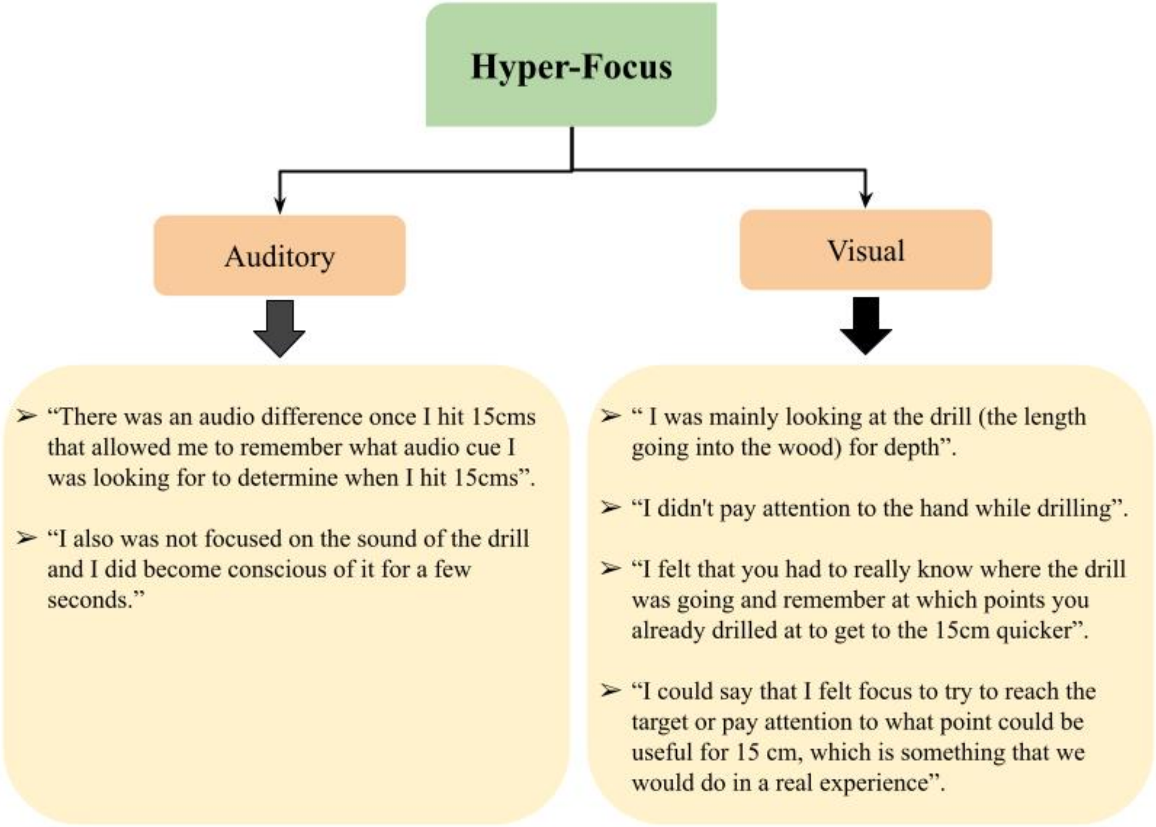
- “It was frustrating at first but once I got it and understood how it worked I felt more confident!”.
- “It was hard to get at first but once get it corrent the first few times you catch on to where to stop”.
- “At times, especially when getting close to completing the 5 consecutive hits, and then you lose that momentum/streak, it was frustrating having to start over. And I felt like I had to restart, and refund that sweet spot of 15 cm. At first you feel like this will not be a difficult task, but you can get frustrated/discouraged when it takes too long”.

- “Wish I could redo it to get a better time”.
- “I liked the aim of the game because allows it to become a challenge and not tires no one”.
- I think being able to see the hole would give rewarding feeling of accomplishment or satisfaction that the task is being done”.

Figure 5.7. A flowchart outlining participants' responses to the identified emotion theme and its subthemes.

5.7.3 Hyper-Focus

The hyper-focus theme includes responses from participants that describe their focus of attention on the task. It includes responses on auditory and visual stimuli that were in the center of attention of the participants and those were outside this focus of attention and therefore missed (Figure 5.8). Responses in the auditory category were only present in the embodiment group, while for the visual category, the responses were equally distributed between the two subject groups. Interestingly, most of the participants reported that they ‘forgot’ about the virtual hand, which is the main subject of this work.



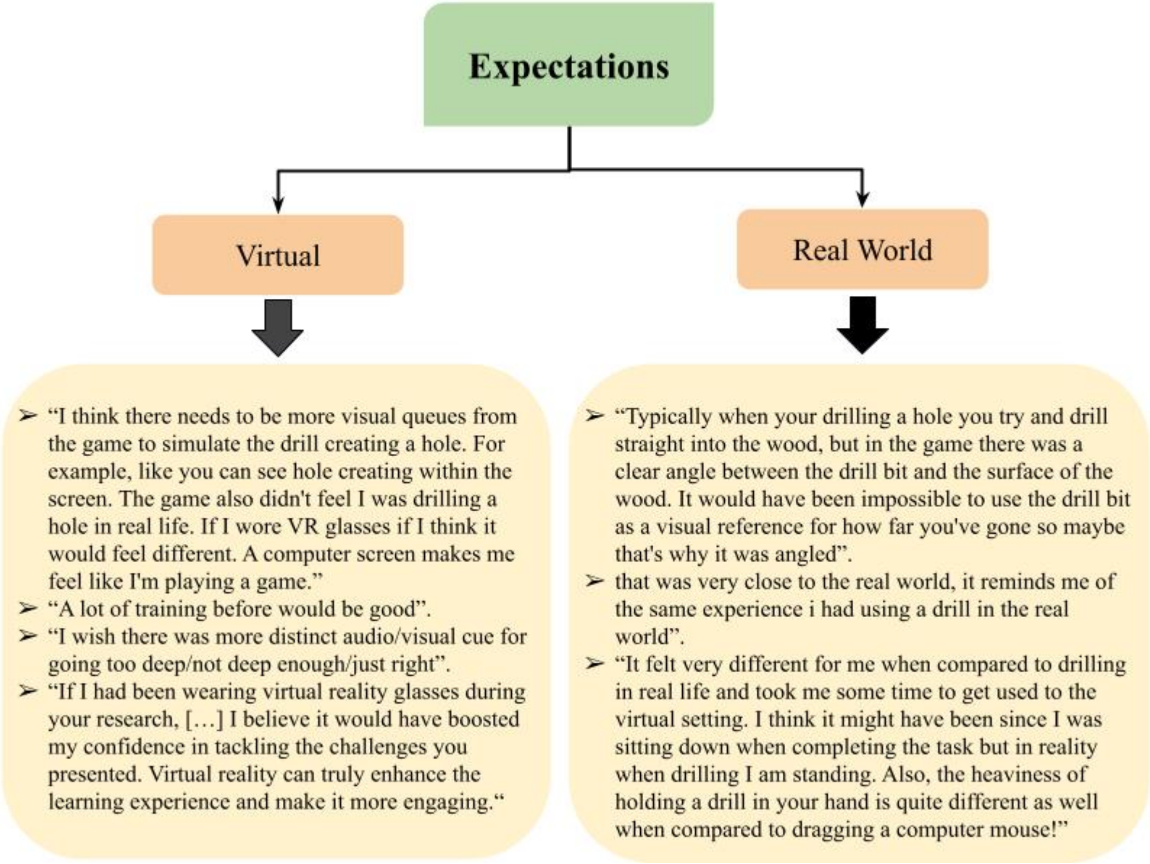
- “There was an audio difference once I hit 15cms that allowed me to remember what audio cue I was looking for to determine when I hit 15cms”.
- “I also was not focused on the sound of the drill and I did become conscious of it for a few seconds.”

- “ I was mainly looking at the drill (the length going into the wood) for depth”.
- “I didn't pay attention to the hand while drilling”.
- “I felt that you had to really know where the drill was going and remember at which points you already drilled at to get to the 15cm quicker”.
- “I could say that I felt focus to try to reach the target or pay attention to what point could be useful for 15 cm, which is something that we would do in a real experience”.

Figure 5.8. A flowchart outlining participants' responses to the hyper-focus theme and its subthemes.

5.7.4 Expectations

The expectations’ theme outlines responses of participants comparing their experiences to those of other virtual platforms such as VR, and those of real-world experience (Figure 5.9). Participants shared their observations of what they usually do differently in the real world when drilling in comparison to drilling in the virtual world, and the responses under the virtual category outline participants' expectations based on what they have experienced using other simulation platforms. These responses are present equally between the two subject groups.



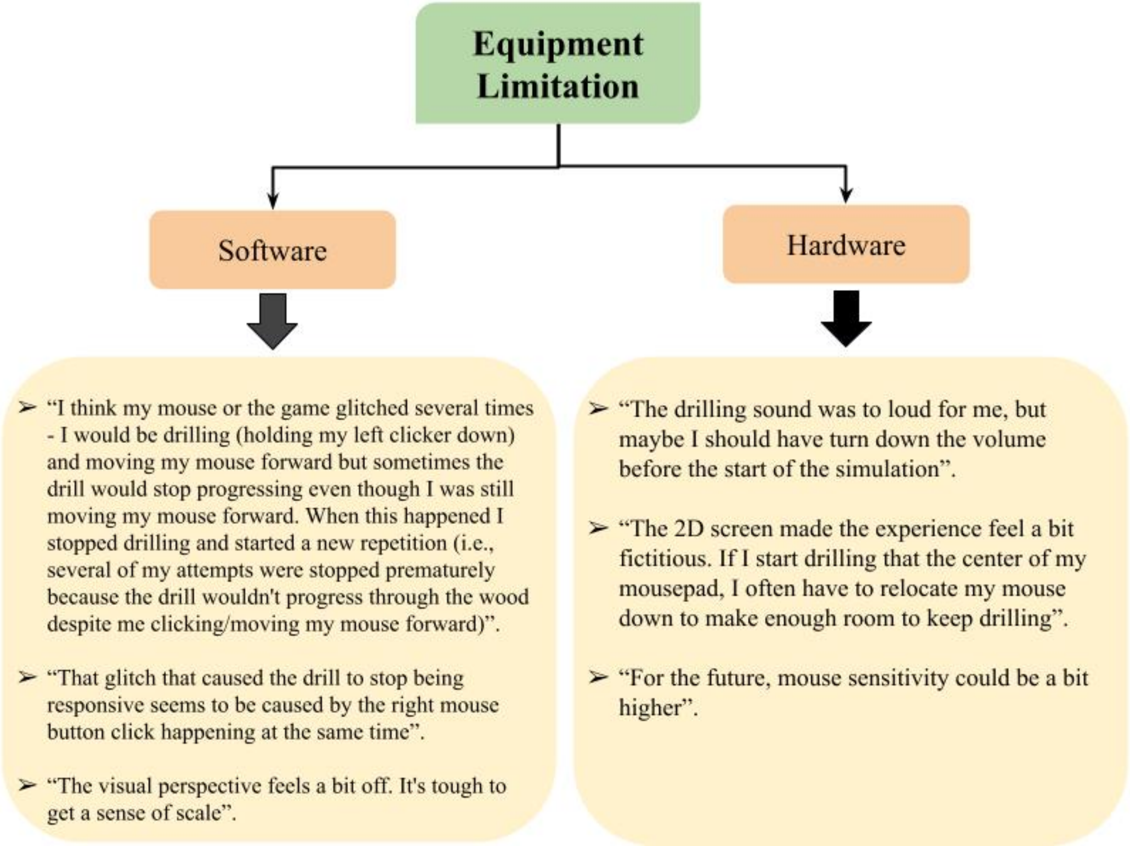
- "I think there needs to be more visual queues from the game to simulate the drill creating a hole. For example, like you can see hole creating within the screen. The game also didn't feel I was drilling a hole in real life. If I wore VR glasses if I think it would feel different. A computer screen makes me feel like I'm playing a game."
- "A lot of training before would be good".
- "I wish there was more distinct audio/visual cue for going too deep/not deep enough/just right".
- "If I had been wearing virtual reality glasses during your research, […] I believe it would have boosted my confidence in tackling the challenges you presented. Virtual reality can truly enhance the learning experience and make it more engaging."

- "Typically when your drilling a hole you try and drill straight into the wood, but in the game there was a clear angle between the drill bit and the surface of the wood. It would have been impossible to use the drill bit as a visual reference for how far you've gone so maybe that's why it was angled".
- that was very close to the real world, it reminds me of the same experience i had using a drill in the real world".
- "It felt very different for me when compared to drilling in real life and took me some time to get used to the virtual setting. I think it might have been since I was sitting down when completing the task but in reality when drilling I am standing. Also, the heaviness of holding a drill in your hand is quite different as well when compared to dragging a computer mouse!"

Figure 5.9. A flowchart outlining participants' responses to the expectations theme and its subthemes.

5.7.5 Equipment Limitation

The equipment limitation theme outlines observations that participants noticed when performing the drilling task in the virtual world using standard computer equipment. These responses under either i) software or ii) hardware (Figure 5.10). The software included limitations that are not completely tangible such as computer/mouse glitches, whereas hardware includes tangible limitations such as monitor and mouse. Responses to this theme seem to be equally observed between the two subject groups.



- “I think my mouse or the game glitched several times - I would be drilling (holding my left clicker down) and moving my mouse forward but sometimes the drill would stop progressing even though I was still moving my mouse forward. When this happened I stopped drilling and started a new repetition (i.e., several of my attempts were stopped prematurely because the drill wouldn't progress through the wood despite me clicking/moving my mouse forward)”.
- “That glitch that caused the drill to stop being responsive seems to be caused by the right mouse button click happening at the same time”.
- “The visual perspective feels a bit off. It's tough to get a sense of scale”.

- “The drilling sound was to loud for me, but maybe I should have turn down the volume before the start of the simulation”.
- “The 2D screen made the experience feel a bit fictitious. If I start drilling that the center of my mousepad, I often have to relocate my mouse down to make enough room to keep drilling”.
- “For the future, mouse sensitivity could be a bit higher”.

Figure 5.10. A flowchart outlining participants' responses to the equipment limitation theme and its subthemes.

Chapter 6. Discussion

6.1 Overview

This chapter consists of three main parts. The first part discusses the results of the study. The second discusses the practical implications of this work, particularly in medical education. The chapter will end with a limitation section that addresses the identified constraints and barriers that may have affected the results of this study.

6.2 Study Discussion

This thesis work explored the effect of embodiment when coupled with pseudo-haptics on task performance and learning using accessible and commonly available computer equipment. An Embedded Mixed Design method was utilized to help answer the research question: What effect, if any, does the sense of embodiment, through the representation of a simulated hand, have on performance and learning of a drilling task when coupled with pseudo-haptics using standard computer equipment (i.e., 2D computer display, mouse, and headphones)?

The results of the study showed that embodiment through the addition of a virtual hand allows for a significantly shorter completion time and number of attempts in comparison to its counterpart non-embodiment condition that consisted of only the drill without a virtual hand. In other words, the addition of the hand significantly increased the speed of acquisition between two participant groups.

Skill acquisition, in psychomotor skill development, normally occurs during the practice stage where the learner has the opportunity to perform the skill until they feel proficient [108]. Following the acquisition stage, a test is normally administered: i) a retention test, a test of performance that assesses the learner's retention of the skill [108], and ii) a transfer test, which assesses the learner's ability to use what they learned in different situations [108]. While the retention test is a test of the learner's memory that retests learners on the same task with the same conditions, the transfer test tests the participants' learning by having them transfer what they learnt to a different condition or situation. This thesis examines the learner's ability to take what they have learnt in the practice session and test its transferability to a different situation such as medical and engineering procedures involving a drilling task. Based on this reasoning, a transfer test was chosen over a retention test, since, in medicine, no two patients or situations are the same, and thus a transfer test will allow for a better practical implication. According to the specificity of learning that states that one learns better that they practiced [108], it was expected that participants who were assigned the same condition as the practice would outperform those who were assigned the new condition, E/E performing better than NE/NE. The addition of the virtual hand, however, does not seem to have a considerable influence on transfer test results even when the average mean of participants in the *embodiment* groups was smaller than that of the *non-embodiment* group. This insignificance could be due to the short retention period between the practice and the transfer test. According to Schmidt et al. (2019), a retention time of 24 hours or more is commonly used, however it is challenging to predict the length of interval between the lasting, permanent learning effect and the temporary effect of the practice [108].

Moreover, this study used proficiency-based learning as the end point of the practice session (achieving performance plateau), which is thought to maximize skill acquisition [114]. At the end of the practice session, all participants became proficient in performing the drilling task. Thus, having a 24-hour retention period between the two sessions might not have been long enough to diminish the temporary effect of the practice to manifest a difference in learning between the two groups, leading to the insignificant results.

Computer equipment limitations may explain moderate effect size observed in both the time to completion and number of attempt results. Multiple participants mentioned that their mouse sensitivity was better, or their mouse pad was preventing them from moving their mouse more freely. In addition, many participants reported a ‘glitch’ that could be due to having a heavy program running on their computer, thus slowing the simulation down. Frustration could also have played a role in the number of attempts participants took to complete the task, qualitative results also show that multiple participants reported that they became frustrated when they lost their progress or when they tried to reach the plateau. Child and Waterhouse (1953), verified by [115], examined the relation between frustration and the quality of performance and found that participants who responded to frustration performed worse than those who did not. They discussed that frustration will lead to other responses that will interfere with performance hence leading to the reduction of performance [116].

In addition to feeling frustrated, participant expectations may have also hindered their performance, particularly when comparing the 2D simulation to participants’ experience in VR (based on qualitative responses from participants). This low expectation might have caused a Pygmalion Effect leading to a lower performance. The Pygmalion Effect is a psychological phenomenon first observed by Rosenthal and Jacobson in 1968 indicating that there's a positive relation between expectation and performance as high expectation leads to high performance and low expectation leads to low performance [117, 118]. Participants with prior VR experience may have low expectations for the 2D simulation, leading to the lack of significance between the groups. Although they used a preliminary sample, a study by Ferreri and Mayhorn (2021) revealed that participants experiencing malfunctioning performed worse and this performance carried over [119]. Ferreri and Mayhorn (2021) discussed that when participants have low expectations and a malfunction occurs, the participants lose motivation causing performance to decrease. This observation by Ferreri and Mayhorn (2021), could also explain the potential moderate effect size observed in this thesis work, particularly for participants who experienced the 'glitch', which could have also translated to the transfer test session leading to the insignificant results.

The embodiment questionnaire results show no significant difference in embodiment scores between the two groups. This may be due to the potential misinterpretation of the questions as outlined in some of the qualitative responses where participants interpreted the sensation felt in their body as 'excitement' and 'curiosity' instead of neurological or muscular sensations. Moreover, being extremely focused drilling the correct depth during the drilling task session, particularly focused on the drill bit portion of the drill as some of the participants mentioned in their qualitative responses, may have hindered the sense of embodiment. "Keep your eyes at the place aimed at and your hand will fetch it [the target]; think of your hand, and you will likely miss your aim" this quote by William James in his book ‘The principles of psychology’ [120] could help explain why no difference in embodiment was observed between the two groups. We, as humans, exhibit selective attention; in other words, we have a limited maximum capacity to the number of things we can do at a given moment [108]. A selective attention, also called intentional selection, refers to the type of attention that one chooses to be purposely allocated to a specific source and inhibiting attention to other sources of information. Two types of focus of attention exist: i) internal focus; and ii) external focus. Internal focus of attention refers to the concentration on body movement, i.e., on the hand when swinging a bat or on the foot when kicking, while external focus on the other hand directs the attention toward the end goal of the movement, i.e., the basketball net or the soccer goal. An external focus of attention was observed in this study (based on the feedback) where participants focus their attention on the drill bit, the shadows or the sound ignoring the rest of the environment including the virtual hand being studied. Some participants were so focused that they “did not even notice the hand was there,” a quote from one of the participants of the study. This hyper-focus creates what is called an ‘inattentional blindness’ where one fails to perceive certain visual stimuli due to being focused on another stimuli (typically visual as well) [108]. This selective paradigm was observed in the ‘gorilla’ experiment by Simons and Chabris in 1999. In this famous experiment, the participants were asked to watch a video of players passing a basketball to each other in two teams, one wearing white shirts and another hearing a black shirt. The participants’ task is to count the number of passes players in white shirts have made ignoring those in black shirts. Sometime during the video, however, a person dressed in a black gorilla costume walked through the middle of the teams, stopped, looked at the camera then walked off the screen[2]. Interestingly, approximately half of the participants who were engaged in counting the number of passes did not see the gorilla [121]. This intentional selection of processing information made the participants unaware of events unrelated to the task even if these events were unusual. Another study by Lugrin et al. (2018) examined the effect of avatar body part visibility (no body part visible for participants in 'none' condition, and only hands and forearm were visible those in 'low' condition group in comparison to those the 'medium' condition group who had a hand, forearm, arm, head, torso, shoulder) on player's experience and performance in VR. They found that the participants were in a high flow state, focusing on completing the game with high performance, and they failed to realize that their avatars had an increased number of body parts. This reduced self-awareness resulted in no significant difference was wound in the performance between the three different experimental conditions [122]. The ability to selectively focus one's attention on specific information allows the filtering of unwanted information to facilitate performance.

It is also interesting to note that multiple participants in the embodiment group reported a 'tingling' sensation when asked to describe the sensation they felt when they saw and interacted with the virtual drill. A tingling sensation was identified as one of the sensations individuals feel when they embody an object. In their study, Medina et al. (2015) reported that when participants experienced embodiment they felt a tingling sensation, a change in weight, and a drop in temperature of their real limbs [123]. More participants in the embodiment group experienced this tingling sensation in their real hand in comparison to participants in the non-embodiment group. Despite this observed

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[2] Refer to https://www.youtube.com/watch?v=vJG698U2Mvo to view the experiment.

‘tingling’ sensation, no significance was observed in the results of the embodiment questionnaire responses. Moreover, the addition of the hand did significantly improve the speed of acquisition in the embodiment group, leaving an important question: why did the embodiment questionnaire not yield significant results even when the representation of the hand improved performance and participants reported a ‘tingling’ sensation when seeing the virtual hand? Goodale and Milner (1992) explained the different pathways that exist for visual perception processing and action. They explain that due to the different processes transpired between the two independently functioning systems, there will be occasions where individuals will not be aware of the visual representation when performing a visuo-motor action, even when this action was perfectly conducted [124]. In the case of this thesis, participants in the embodiment group had a significantly higher speed of acquisition than those in the non-embodiment group, although the embodiment score was not significantly different. It could have been that visuo-motor action has caused a superordination between the two processes preventing participants from consciously being aware of their perception of embodiment.

Finally, although it was expected that the embodiment group would score a higher engagement score than the non-embodiment group. For the similar reasons mentioned earlier, low expectation and frustration may have also played a role in the insignificance of the engagement responses. Regardless, most participants stated their excitement toward the virtual simulation, claiming it was ‘fun,’ ‘a great experience,’ and that they wanted to perform better and have better scores, indicating that overall participants enjoyed participating in study.

6.3 Practical Implications

This work builds on the work of Melaisi et al. (2018) by moving away from the use of costly haptic devices using pseudo-haptics and on Ning et al.'s work by adding the sense of embodiment through the representation of a virtual hand. Both pseudo-haptically induced kinesthetic feedback and embodiment through the representation of the virtual hand enhanced the speed of acquisition of the virtual drilling task.

Coupling embodiment with pseudo-haptics using standard computer equipment did increase the acquisition speed of the simulated drilling task. This finding could allow for cost-effective psychomotor skills development in medical simulation, particularly in rural areas or remote learning settings, where access to high-end haptic devices and head-mounted displays is unavailable. This may, with more testing, lead to a set of best practices to guide designers and developers of VLEs who wish to incorporate pseudo-haptics into their VLEs and allow for accessible, affordable, and portable psychomotor skills development.

6.4 Limitations

One major limitation identified in this study is the difference in computer equipment functioning. Although it allowed for greater access to the VLE with the convenience of participating from home, the use of different equipment might have caused additional frustration when malfunction occurred such as the perceived 'glitch' or the difference in mouse sensitivity and could have affected the results of the study. Moreover, although steps were taken to limit any distractions participants may have faced during the study, the lack of control of the participant’s environment could have also influenced the results.

Another limitation is the lack of consideration of the participants' dominant hand. The serious game currently portrays a right-handed operation of the drill and if the participant is left-handed dominant, they may operate the mouse with their left hand and cause a misalignment between the drill and their hand, preventing any perceived embodiment. Another misalignment that may have occurred during the study is the camera misalignment due to the difference in participant’s monitor size. The visual perspective needed to be in 1PP positioned in such a way, so the participant seems they are drilling in real life. Although Unity3D tries to adjust the view based on the monitor, this adjustment might not be exactly accurate to the eye level of the participant causing misalignment and leading to a loss of embodiment.

It is also important to mention that responses on questionnaires highly depend on participants’ interpretation of the questions, which might affect the results. This was observed in the embodiment questionnaire open response to the sensation question, where participants answered ‘excitement’ and ‘curiosity’ to that question instead of outlining bodily sensations that they have experienced.

Finally, the limited sample size is another limitation to this study, particularly the one for the transfer test where only ten participants were recruited in each group. Increasing the sample size could also decrease the variability on the number of attempt variables, rendering it a normal distribution.

Chapter 7. Conclusions

This thesis examined the effect of embodiment on performance and learning when coupled with pseudo-haptics within a simple virtual drilling task. Embodiment has been studied within fully immersive VLEs but is overlooked when considering simple 2D-based VLEs and with respect to pseudo-haptics. To address this gap, a virtual simulation was developed and tested by 40 participants equally divided into two experimental groups to examine whether the addition of a virtual hand affected performance and learning of the drilling task.

The results indicated that the time spent and the number of attempts to complete the task was significantly smaller in the embodiment group than the non-embodiment group indicating there was an effect on speed of acquisition. There were multiple qualitative responses of participants, such as the feeling of frustration, and equipment limitation that occurred while performing the task, which might have impacted the effect size observed on these two qualitative factors. Although the overall score indicated no embodiment difference between the two groups, more participants in the embodiment group reported a tingling sensation, which could be associated with embodiment [123]. Finally, both experimental groups learned the task equally and were equally engaged in the drilling task.

Future Direction

Taking results of the study and participants' feedback and comments into consideration, future work will focus on controlling the equipment used in the study by inviting the participants to conduct the study using a standard computer set up in a lab or set specific requirement criteria for equipment participants own at home. The virtual simulation should also be updated to include left-hand usability. A 'how to play' session should be added to the beginning of the practice session so that participants have a better understanding of how to play the serious game. This would allow the participants to be more prepared for the practice session and hopefully lessen the sense of frustration while performing the practice. Moreover, adding description or instructions to each of the questionnaire's items to clarify what the statement means, would make the statements more concise and clearer to lessen the chance of misinterpretation by the participants.

Finally, these results are preliminary, and a larger sample is suggested to increase the number of participants in each group to provide a larger dataset. While moving this simulation to VR is a potential option that might raise participants' expectation and hence lead to better results, the availability, affordability, and convenience standard computer brings still makes it worth investing in. The first step is to overcome the limitation discussed in this thesis work to ensure concrete results before moving to fully immersive VR. Achieving the sense of embodiment coupled with pseudo-haptics using standard computers will lead to a greater convenience and availability in medical simulation education, particularly in rural areas.

Chapter 8. References

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Appendices

Appendix A. Literature Search

The literature review in this thesis followed the methodological framework for scoping studies published by Arksey and O'Malley (2005). The framework describes five stages of finding and evaluating relevant articles: i) identify the research question, ii) identify relevant studies, iii) select the studies, iv) chart the data, and v) collate, summarize, and report the results [125].

i. **Identify the research question:** Identifying the important aspect of the research question will guide the literature search strategy. In the case of this thesis, the research question: *What effect, if any, does the sense of embodiment through the representation of a simulated hand have on the performance and learning of a drilling task when coupled with pseudo-haptics using a standard 2D computer display (visual cues), mouse (kinesthetic cues) and headphones (auditory cues)?* The important aspects identified and acted as keywords are: "embodiment" OR "the sense of embodiment;" "pseudo-haptics;" "multimodal" to account for the three cues (visual, kinesthetics and auditory).

ii. **Identify relevant studies**: Electronic databases: 'Google Scholar,' 'Ontario Tech University Library Database' and 'Research Gate,' were used to find two articles as a starting point. Articles between the years 2012 and 2023 were originally examined to identify relevant topics in each of the key aspects of the research question. Dr. Bill Kaprolos provided two more articles. These articles were then entered into the artificial intelligence (AI) search engine 'ResearchRabbit.' It generated a web of articles that supported my research study.

iii. **Study selection:** I manually reviewed each abstract from the articles generated by ‘ResearchRabibit’ to assess their suitability to support the research question. The abstracts chosen were then read in full, by me. Following reading the full article, a few were discarded due to talking about ‘cognitive embodiment’ and if they were not under the fields of Computer Science and/or Health Science.

iv. **Charting the data:** Articles identified in step (iii) were relevant entered into Zotero and separated by keywords. The articles were then re-read with a focus on the key aspects using a colour-coded system.

v. **Collate, summarize, and report the results:** Using the colour-coded system conducted in stage (iv), articles were then collated together and summarized under subheadings in Chapter 2 of this thesis under subheadings.

Appendix B. Invitation To Participate in the Study

B1. Recruitment emails

1.1 Ontario Tech University Students:

Hello [Name],

You are invited to participate in a voluntary research study, **Appropriate Audio and Visual Cues to Simulate Drilling**, which examines the simulation of a drilling task (drilling through a block wood using a drill) in the virtual domain using visual and auditory cues. The experiment will be carried out remotely via the Google Meet platform, and using standard home computer equipment (e.g., mouse, keyboard, headphones, and monitor).

Participation in this research study will take approximately **20 minutes to complete**. Your task as a participant in this experiment will require you to perform a drilling task that involves drilling through a piece of wood to a pre-defined depth under one auditory and one of two visual cues in a virtual environment. The experiment consists of a training session and a transfer test followed by two online questionnaires about the experimental experience you completed.

In the training phase, you will be asked to drill to a depth of 15 cm into a virtual block of wood until you are able to drill to that length five consecutive times, under an auditory and visual condition randomly pre-determined before the start of the session. This will allow you to familiarize yourself with the tool and prepare you for the transfer test phase. Once you successfully complete the training session, you will be asked to fill out two online questionnaires then come back after 24h for a transfer test. A visual condition will be assigned (could be the same or a different one), and you will be asked to drill 9 cm ONCE. At the end of the experiment, you will be asked to send the data in the form of a text file back to the experimenter.

Since the experiment includes auditory cues, you must not have any issues with your hearing to participate in the experiment. Furthermore, if you are currently taking any course with Dr. Bill Kapralos or have never used a drill to drill through some material in the past, you are not eligible to participate in the experiment.

Participation in this study is completely voluntary (you will not be paid for your participation), and this experiment does not have any bearing or influence on your physical health, privacy/reputation, and/or academic evaluation/standing. At any time during the study, you may decline to answer a question and may withdraw from the experiment altogether for whatever reason without any explanation or fear of repercussion. You may also withdraw from the experiment at any time within seven days of completing the experiment. If you do choose to withdraw from the experiment for any reason, your data will be deleted and not considered further. Your data will not be analyzed or viewed until seven days after the last participant has completed the experiment. Your data will be anonymized. Only Dr. Kapralos will have access to the data upon completion of this study. Every effort will be made on behalf of the facilitators to avoid any invasion of your privacy.

If you have any questions regarding your rights as a participant or have any concerns about this study, please contact the Research Ethics Office at researchethics@ontariotechu.ca. This study has been reviewed by the Ontario Tech University Research Ethics Board, **assigned REB #16280 on April 17, 2023**.

This message is being sent on behalf of Dr. Bill Kapralos (Principal Investigator) and Sandy Abdo (Student Lead). Participation is entirely **voluntary** and there is no obligation participate. If you are interested in participating or have any further questions, contact Sandy Abdo, at sandy.abdo@ontariotechu.net.

1.2 Recruits from outside the university:

Hello [Name],

You are invited to participate in a voluntary research study, **Appropriate Audio and Visual Cues to Simulate Drilling**, which examines the simulation of a drilling task (drilling through a block wood using a drill) in the virtual domain using visual and auditory cues. The experiment will be carried out remotely via the Google Meet platform, and using standard home computer equipment (e.g., mouse, keyboard, headphones, and monitor).

Participation in this research study will take approximately **20 minutes to complete**. Your task as a participant in this experiment will require you to perform a drilling task that involves drilling through a piece of wood to a pre-defined depth under one auditory and one of two visual cues in a virtual environment. The experiment consists of a training session and a transfer test followed by two online questionnaires about the experimental experience you completed.

In the training phase, you will be asked to drill to a depth of 15 cm into a virtual block of wood until you are able to drill to that length five consecutive times, under an auditory and visual condition randomly pre-determined before the start of the session. This will allow you to familiarize yourself with the tool and prepare you for the transfer test phase. Once you successfully complete the training session, you will be asked to fill out two online questionnaires then come back after 24h for a transfer test. A visual condition will be assigned (could be the same or a different one), and you will be asked to drill 9 cm ONCE. At the end of the experiment, you will be asked to send the data in the form of a text file back to the experimenter.

Since the experiment includes auditory cues, you must not have any issues with your hearing to participate in the experiment. Furthermore, if you have never used a drill to drill through some material in the past, you are not eligible to participate in the experiment.

Participation in this study is completely voluntary (you will not be paid for your participation), and this experiment does not have any bearing or influence on your physical health, privacy/reputation, and/or academic evaluation/standing. At any time during the study, you may decline to answer a question and may withdraw from the experiment altogether for whatever reason without any explanation or fear of repercussion. You may also withdraw from the experiment at any time within seven days of completing the experiment. If you do choose to withdraw from the experiment for any reason, your data will be deleted and not considered further. Your data will not be analyzed or viewed until seven days after the last participant has completed the experiment. Your data will be anonymized. Only Dr. Kapralos will have access to the data upon completion of this study. Every effort will be made on behalf of the facilitators to avoid any invasion of your privacy.

If you have any questions regarding your rights as a participant or have any concerns about this study, please contact the Research Ethics Office at researchethics@ontariotechu.ca. This study has been reviewed by the Ontario Tech University Research Ethics Board, **assigned REB #16280 on June 14, 2023**.

This message is being sent on behalf of Dr. Bill Kapralos (Principal Investigator) and Sandy Abdo (Student Lead). Participation is entirely **voluntary** and there is no obligation participate. If you are interested in participating or have any further questions, contact Sandy Abdo, at sandy.abdo@ontariotechu.net.

B2. Consent form

Consent Form to Participate in a Research Study

Title of Research Study: Appropriate Audio and Visual Cues to Simulate Drilling

Name of Principal Investigator (PI): Bill Kapralos

PI's contact number(s)/email(s): 905-721-8668 x2882 (or email: bill.kapralos@ontariotechu.ca)

Name(s) of Co-Investigator(s), Faculty Supervisor, Student Lead(s), etc., and contact number(s)/email(s):

Sandy Abdo (Student Lead), sandy.abdo@ontariotechu.net

Departmental and institutional affiliation(s): Faculty of Business and IT, Ontario Tech University; Faculty of Health Sciences, Ontario Tech University

Introduction:

You are invited to participate in a research study entitled *Appropriate Audio and Visual Cues to Simulate Drilling*. Please read the information about the study presented in this form below. The form includes details on study's procedures, risks, and benefits that you should know before you decide if you would like to take part. You should take as much time as you need to make your decision. You should ask the Principal Investigator (PI) or study team to explain anything that you do not understand and make sure that all your questions have been answered before signing this consent form. Before you make your decision, feel free to talk about this study with anyone you wish including your friends and family. Participation in this study is voluntary.

This study has been reviewed by the University of Ontario Institute of Technology (Ontario Tech University) Research Ethics Board #16280 on April 17, 2023, and updated on June 14, 2023.

Purpose and Procedure:

Purpose:

Current virtual simulations and serious games focus primarily on cognitive skills development, typically ignoring psychomotor/technical skills development altogether. This is due to two main reasons.

First, the complexities and costs associated with simulating the sense of touch. Although consumer-grade haptic devices (used to simulate the sense of touch) are readily available, they are restrictive with respect to their available degrees-of-freedom (DOF), the electro-mechanical characteristics of sensors and actuators they include. These limitations do not allow such devices to be used in many haptic-based applications, such as applications where high-fidelity haptic interaction is essential, including medical education. Therefore, we aim to explore whether a haptic based virtual environment could be simulated using only the appropriate auditory and visual cues, as well as common computer devices in the home (headphones, mouse, monitors, etc.) in the absence of haptic devices.

Second, the lack of coupling of psychomotor skills development with embodiment. The sense of embodiment is described as the perceived processing of a virtual body as being part of one's physical body, which is fundamental to psychomotor development. One cannot acquire any new skill without being bodily present to generate, control, and exploit movement. Despite the necessity of embodiment for psychomotor skill acquisition, many studies have overlooked this fundamental aspect. Research has found that simulating a real human hand on an avatar representing the user in virtual reality (VR) enhances the feeling of embodiment, however, there is no apparent research in the medical field that has examined embodiment using easily accessible (standard) computer equipment.

In this study, we are focusing on a drilling task, and more specifically, the simulation of drilling through a block of wood using a virtual drill. The purpose of this study/experiment is to examine whether the effect of embodiment on pseudo-haptics during a simple virtual drilling task using standard computer equipment available to most people in their home (e.g., headphones, mouse, etc.). In order to participate in this study/experiment, we require that you have prior experience using a drill and that you do not have any problems/issues with your hearing (at least that you are aware of).

Procedures:

Since the experiment will be conducted virtually/remotely, you must have a mouse, headphones/earbuds, and a monitor/display with the resolution set 1920 x 1080 to complete the experiment. The experimenter will meet you remotely via Google Meet (https://meet.google.com/) and provide a brief verbal explanation of the experiment and required tasks to you via this online meeting. At the same time, you will receive an executable file (the experiment application developed using the Unity 3D game engine) via email from the experimenter. The study is comprised of two parts: a training session and a transfer test. Prior to the transfer test, you will start by completing a training session to familiarize yourself with the process (i.e., the drilling simulation). You will perform the training under one sound and one of two visual cues. More specifically, the visual conditions are i) just the drill, ii) a hand holding the drill. The auditory condition is dynamic drilling sound where the sound corresponds to a drill drilling through wood. Prior to the start of the experiment, you will be randomly placed in a group where you will be exposed to one of the two visual conditions and the auditory condition (i.e., one of the conditions described above). The training session will involve the following: you will be presented with a visual of the virtual drilling scenario and you will be asked to move the drill into the block of (virtual) wood using the movement of the mouse. **If the visual condition happens to be 'hand holding the drill' you will first be asked to choose the hand's skin tone that matches your own.** You will be asked to drill 15 cm through a virtual piece of wood until you drill the correct length five times consecutively. Once successfully completing the practice session, you will be asked to send the file data back to the experimenter and complete two online questionnaires.

After **24-hours** from completing the training session, you will start the transfer test phase. The testing phase will ask you to drill 9 cm ONE time into the virtual block of wood under different sound and visual conditions. You will be once again put in a group with different visual and sound conditions. After completion of the experiment, the experimenter will instruct you to email the file back to them.

You will be able to control the virtual drill using your 2D mouse, The left button will activate the drill, moving the mouse will move it toward/away from the block of wood, and releasing the left button will deactivate it. For each trial, when you release the mouse, the current drilling depth (the drill bit into the wood) is recorded, and a text-formatted file is automatically generated on your computer. This file will include the experimental conditions (visual, and auditory) used for each trial, the number of trials and total time until you completed the task, and the drill depths you drilled into the wood board under these settings.

The total estimated time to complete the experiment to be approximately 20 minutes.

Potential Benefits:

Participating in this project you will gain an understanding and appreciation for the work being completed by graduates in the Health Informatics graduate program at Ontario Tech University. Furthermore, you may gain new knowledge on immersive technologies in general. You may also find the study rewarding, given that the work may be a tool used to provide better, more effective educational tools that will ultimately lead to better-trained professionals.

Potential Risks or Discomforts:

You will be asked to use a pair of headphones, mouse, and monitor to complete this experiment. During this experiment, drilling sounds will be presenting, and sounds will be presented to them over headphones. The sound level will be set to 65 dB initially (the level of typical conversation which falls between the range of 60-70 dB) and you will be asked to adjust the volume of their computer to a comfortable level. We do not anticipate any issues with this, but you will be able to remove yourself from the experiment at any point without any repercussions.

Use and Storage of Data:

The data you generated in the experiment will be collected in order to analyze the impact of auditory and visual feedback in a virtual reality environment. Your data will be anonymized. ANONYMIZED DATA means that identifying information is completely removed and your responses/results will only be identified with a code not linked to you personally. All raw data will be collected by Student Lead Sandy Abdo on her computer. After analyzing the data and drawing any conclusions, Sandy will send the original data to Dr. Bill Kapralos. Then, this data will be kept in an encrypted zip folder on Bill Kapralos' computer, which further requires a password to log in only known by Professor Kapralos. It will also be "backed-up" on a storage disk drive (owned/maintained by Dr. Bill Kapralos). This back-up disk is currently kept in Bill Kapralos' home office in a secure filing cabinet and is not accessed by anyone else. At the end of the process, Sandy will delete all the raw data about the experiment from her computer to ensure that the data only exists on Dr. Bill Kapralos' computer and the storage disk drive.

All information collected during this study, including your personal information (e.g., your signature on the consent form) will be kept confidential and will not be shared with anyone outside the study unless required by law. You will not be named in any reports, publications, or presentations that may come from this study.

Confidentiality:

Your privacy shall be respected. No information about your identity will be shared or published without your permission, unless required by law. Confidentiality will be provided to the fullest extent possible by law, professional practice, and ethical codes of conduct. The experiment will be conducted by a graduate student working under the supervision of Dr. Bill Kapralos, and any information collected will be used to develop a thorough understanding of the interaction of sound and haptic fidelity perception. All data will be anonymized and will be kept by Dr. Bill Kapralos on his computer and backed-up on a hard disk that is accessed only by Dr. Bill Kapralos and stored in a secure filing cabinet.

Every effort will be made on behalf of the experimenters to avoid any invasion of your privacy. Please not that although confidentiality cannot be guaranteed while data is transferred over email, your data will be anonymized when transferred and therefore, you cannot be identified.

Voluntary Participation:

Your participation in this study is voluntary and you may partake in only those aspects of the study in which you feel comfortable. You may also decide not to be in this study, or to be in the study now, and then change your mind later. You may leave the study at any time without any consequences. You will be given information that is relevant to your decision to continue or withdraw from participation. Such information will need to be subsequently provided. You may refuse to answer any question you do not want to answer, or not answer an interview question by saying, “pass”.

Right to Withdraw:

At any time during the experiment, you may decline to answer a question and may withdraw from the study altogether at any point for whatever reason without any fear of repercussion. You may also choose to withdraw after completing the study. If you choose to withdraw, you may do so by letting the experimenter know that you wish to withdraw. If you withdraw from the research project at any time, any data or human biological materials that you have contributed (via the participant number) will be removed from the study and you do not need to offer any reason for making this request.”

Conflict of Interest:

Researchers have an interest in completing this study. Their interests should not influence your decision to participate in this study. If you are currently taking any courses with Dr. Bill Kapralos, or taking any courses in which, the Student Lead/experimenter (Sandy Abdo) is the Teaching Assistant for during the experimental period (or you know you will be taking a course with Dr. Bill Kapralos in the future), you will not be invited to participate in the experiment.

Compensation, Reimbursement, Incentives:

There will be no compensation for participating in the experiment as participating in the experiment is completely on a voluntary basis (i.e., you will not receive any monetary reward at the end of the experiment). If you opt out, you will not suffer any financial consequences.

Debriefing and Dissemination of Results:

The results of the experiment will eventually be reported in the defense of Student Lead Sandy Abdo's thesis in the form of a presentation and presented in Sandy’s Master’s thesis. If you find the information obtained from this experiment interesting, you can request a copy of the final report by emailing Dr. Kapralos (bill. kapralos@ontariotechu.ca) at any time.

Participant Rights and Concerns:

Please read this consent form carefully and feel free to ask the researcher any questions that you might have about the study. If you have any questions about your rights as a participant in this study, complaints, or adverse events, please contact the Research Ethics Office at (905) 721-8668 ext. 3693 or at researchethics@ontariotechu.ca. If you have any questions concerning the research study or experience any discomfort related to the study, please contact Dr. Bill Kapralos at 905-721-8668 x2882 (or email: bill.kapralos@ontariotechu.ca).

By signing this form, you do not give up any of your legal rights against the investigators, sponsor or involved institutions for compensation, nor does this form relieve the investigators, sponsor or involved institutions of their legal and professional responsibilities."

Consent to Participate:

I (please print your participant number here), participant number ________________ have read the consent form and understand the study being described; I have had an opportunity to ask questions and those questions have been answered. I am free to ask questions about the study in the future; I freely consent to participate in the research study, understanding that I may discontinue participation at any time without penalty. A copy of this consent form has been made available to me.

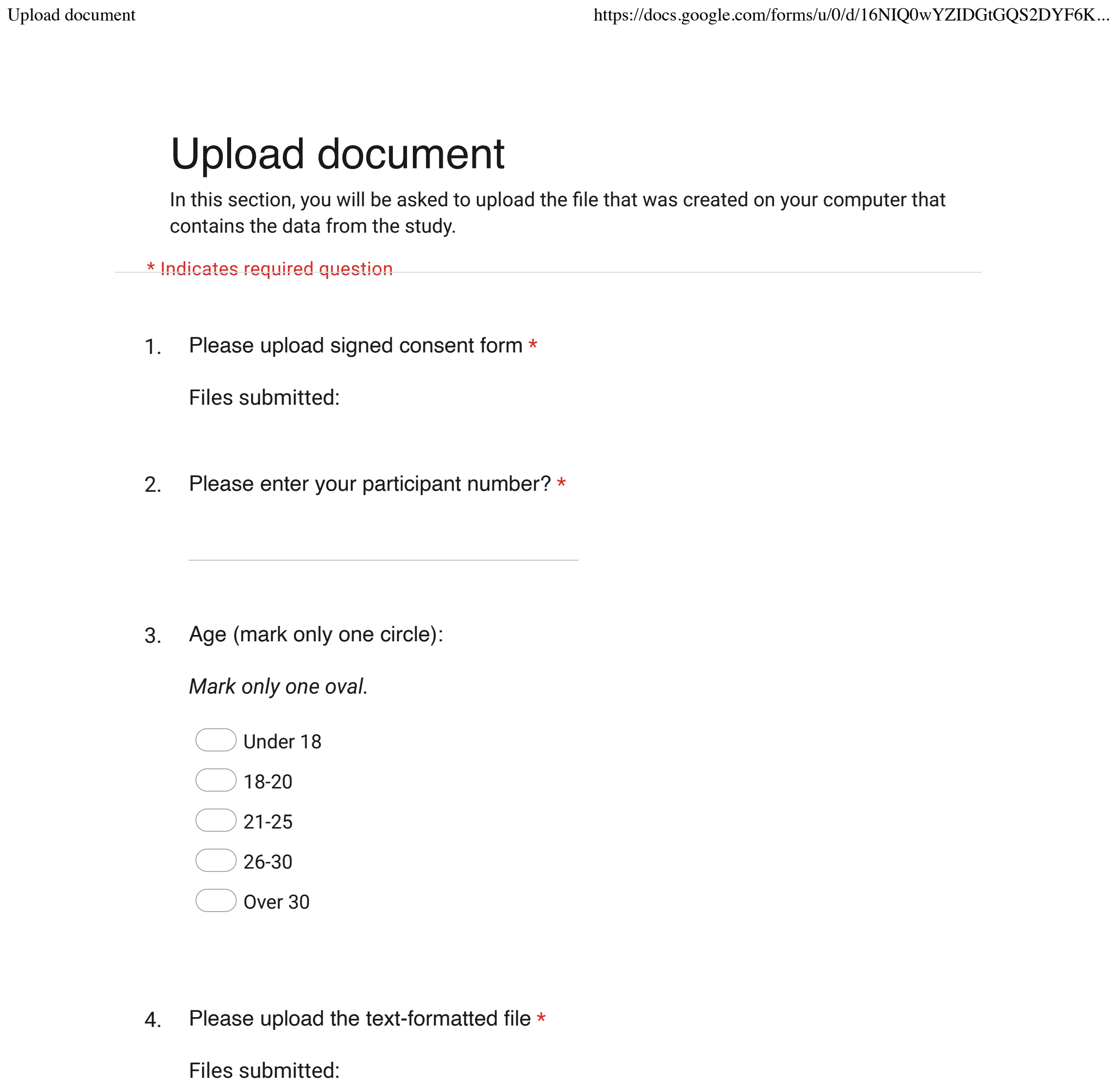
I understand that I have been selected to participate in this study. Participation involves me participating in the study described above. I understand that my honesty and openness is very important to further development of the virtual drilling simulation described earlier. I also understand that as a participant in this experiment, I am not waiving any of my legal rights. I agree to participate in this study and will keep a copy of this consent form for my personal records.

Participant Signature: ____________________________, Date: ____________________________.

Witness Signature: ____________________________, Name: ______________________________,

Appendix C. Questionnaires

C1. First Page



Upload document https://docs.google.com/forms/u/0/d/16NIQ0wYZIDGtGQS2DYF6K...

Upload document

In this section, you will be asked to upload the file that was created on your computer that contains the data from the study.

* Indicates required question

1. Please upload signed consent form *

   Files submitted:

2. Please enter your participant number? *

   ____

3. Age (mark only one circle):

   Mark only one oval.

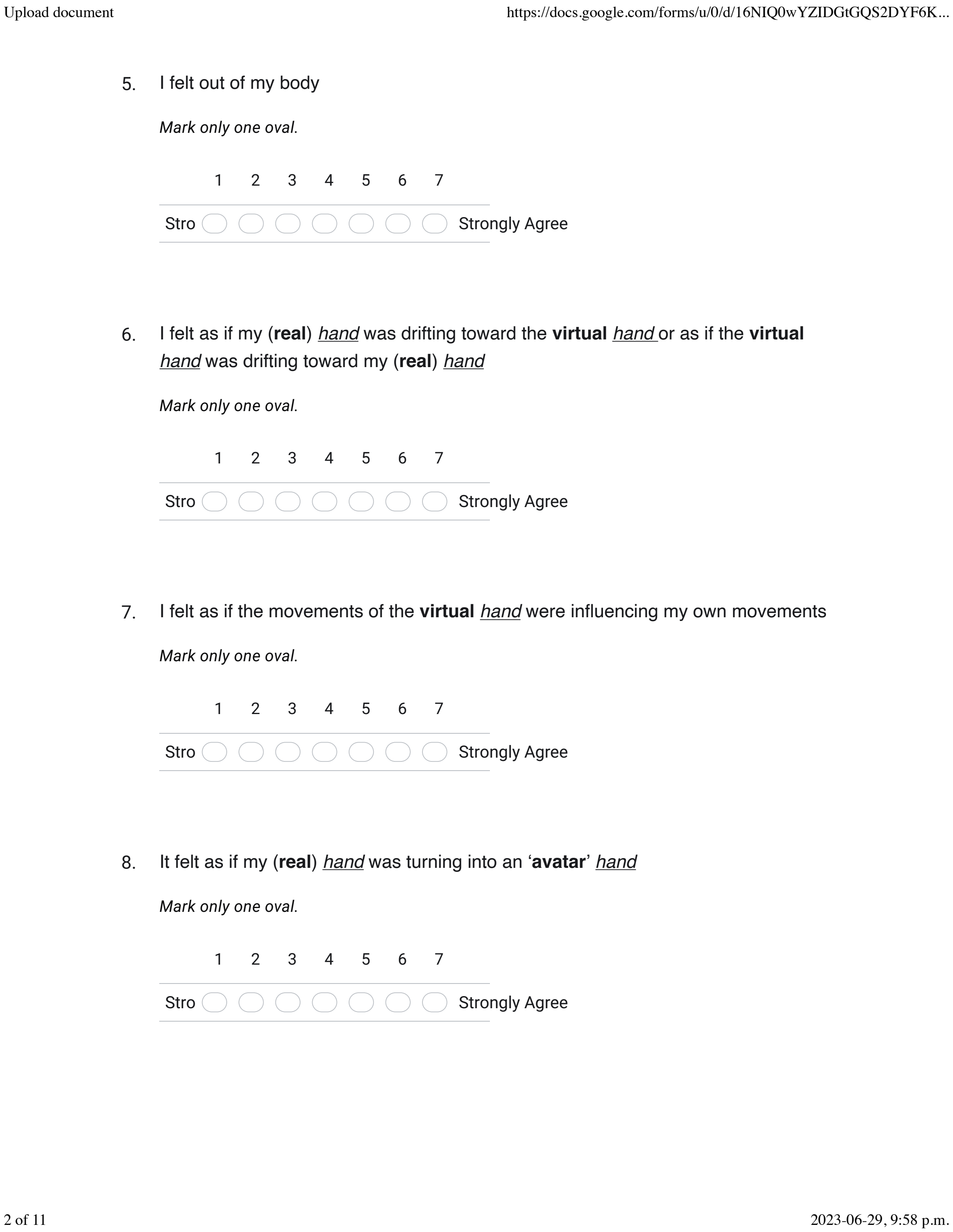
   ○ Under 18
   ○ 18-20
   ○ 21-25
   ○ 26-30
   ○ Over 30

4. Please upload the text-formatted file *

   Files submitted:

C2. Embodiment Questionnaire

1.1 Embodiment Questionnaire for Virtual Hand:



5. I felt out of my body

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

6. I felt as if my (**real**) *hand* was drifting toward the **virtual** *hand* or as if the **virtual** *hand* was drifting toward my (**real**) *hand*

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

7. I felt as if the movements of the **virtual** *hand* were influencing my own movements

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

8. It felt as if my (**real**) *hand* was turning into an ‘**avatar**’ *hand*

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

9. At some point it felt as if my **real** *hand* was starting to take on the posture or shape of the **virtual** *hand* that I saw

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

10. I felt as if my (**real**) *hand* had changed

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

11. I felt a sensation in my body when I saw the **virtual** hand

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

12. If you felt a sensation in your body when you saw the **virtual** hand, what sensation did you feel?

13. I felt that my **own** *hand* could be affected by the **virtual** *drill*

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

14. At some point it felt that the **virtual** *hand* resembled my own (**real**) *hand*, in terms of shape, skin tone or other visual features

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

15. I felt as if the **virtual** *hand* was my (**real**) hand

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

16. I felt as if my (**real**) *hand* was located where I saw the **virtual** *hand*

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

17. I felt like I could control the **virtual** *hand* as if it was my **own** *hand*

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

18. It seemed as if I felt the touch of the **virtual** *drill* in the location where I saw the **virtual** *hand* touched

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

19. It seemed as if my (**real**) *hand* was touching the **virtual** *drill*

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

20. It seemed as if the touch I felt was caused by the **virtual** drill touching the **virtual** hand

Mark only one oval.

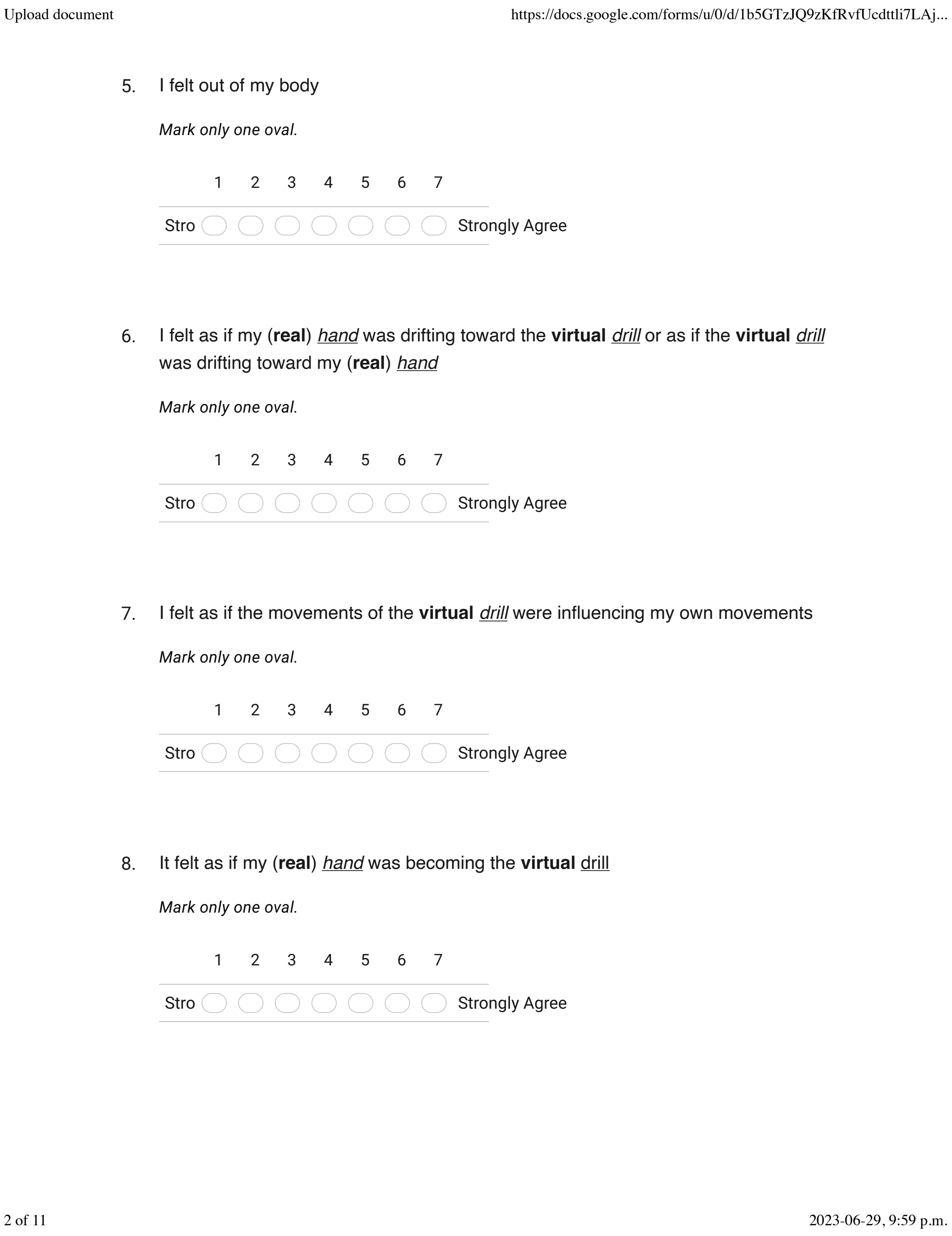
	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

21. Please check that you answered all the questions you wish to answer *

Mark only one oval.

○ I checked, and I am ready to move on to the next section

1.2 Embodiment Questionnaire for Virtual Drill:



5. I felt out of my body

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

6. I felt as if my (**real**) *hand* was drifting toward the **virtual** *drill* or as if the **virtual** *drill* was drifting toward my (**real**) *hand*

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

7. I felt as if the movements of the **virtual** *drill* were influencing my own movements

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

8. It felt as if my (**real**) *hand* was becoming the **virtual** drill

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

9. At some point it felt as if my **real** *hand* was starting to take on the posture or shape of the **virtual** *drill* that I saw

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

10. I felt as if my (**real**) *hand* had changed

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

11. I felt a sensation in my body when I saw the **virtual** *drill*

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

12. If you felt a sensation in your body when you saw the **virtual** *drill*, what sensation did you feel?

13. I felt that my **own** *hand* could be affected by the **virtual** *drill*

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

14. At some point it felt that the **virtual** *drill* resembled my own (**real**) *hand*, in terms of shape, skin tone or other visual features

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

15. I felt as if the **virtual** *drill* was my (**real**) hand

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

16. I felt as if my (**real**) *hand* was located where I saw the **virtual** *drill*

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

17. I felt like I could control the **virtual** *drill* as if it was my **own** *hand*

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

18. It seemed as if I felt the touch of the **virtual** *drill* in the location where I saw the **virtual** *drill*

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

19. It seemed as if my (**real**) *hand* was touching the **virtual** *drill*

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

20. It seemed as if the touch I felt was caused by the **virtual** *drill*

Mark only one oval.

	1	2	3	4	5	6	7	
Stro	○	○	○	○	○	○	○	Strongly Agree

21. Please check that you answered all the questions you wish to answer *

Mark only one oval.

○ I checked, and I am ready to move on to the next section

C3. GEQ

Survey 2

Please fill out the following Survey containing 19 questions

22. I lost track of time

Mark only one oval.

	1	2	3	
No	○	○	○	Yes

23. Things seem to happen automatically

Mark only one oval.

	1	2	3	
No	○	○	○	Yes

24. I feel different

Mark only one oval.

	1	2	3	
No	○	○	○	Yes

25. I feel scared

Mark only one oval.

	1	2	3	
No	○	○	○	Yes

26. The game feels real

Mark only one oval.

	1	2	3	
No	○	○	○	Yes

27. If someone talks to me, I don’t hear them

Mark only one oval.

	1	2	3	
No	○	○	○	Yes

28. I get wound up

Mark only one oval.

	1	2	3	
No	○	○	○	Yes

29. Time seems to kind of stand still or stop

Mark only one oval.

	1	2	3	
No	○	○	○	Yes

30. I feel spaced out

Mark only one oval.

	1	2	3	
No	○	○	○	Yes

31. I don’t answer when someone talks to me

Mark only one oval.

	1	2	3	
No	○	○	○	Yes

32. I can’t tell that I’m getting tired

Mark only one oval.

	1	2	3	
No	○	○	○	Yes

33. Playing seems automatic

Mark only one oval.

	1	2	3	
No	○	○	○	Yes

34. My thoughts go fast

Mark only one oval.

	1	2	3	
No	○	○	○	Yes

35. I lose track of where I am

Mark only one oval.

	1	2	3	
No	○	○	○	Yes

36. I play without thinking about how to play

Mark only one oval.

	1	2	3	
No	○	○	○	Yes

37. Playing makes me feel calm

Mark only one oval.

	1	2	3	
No	○	○	○	Yes

38. I play longer than I meant to

Mark only one oval.

	1	2	3	
No	○	○	○	Yes

39. I really get into the game

Mark only one oval.

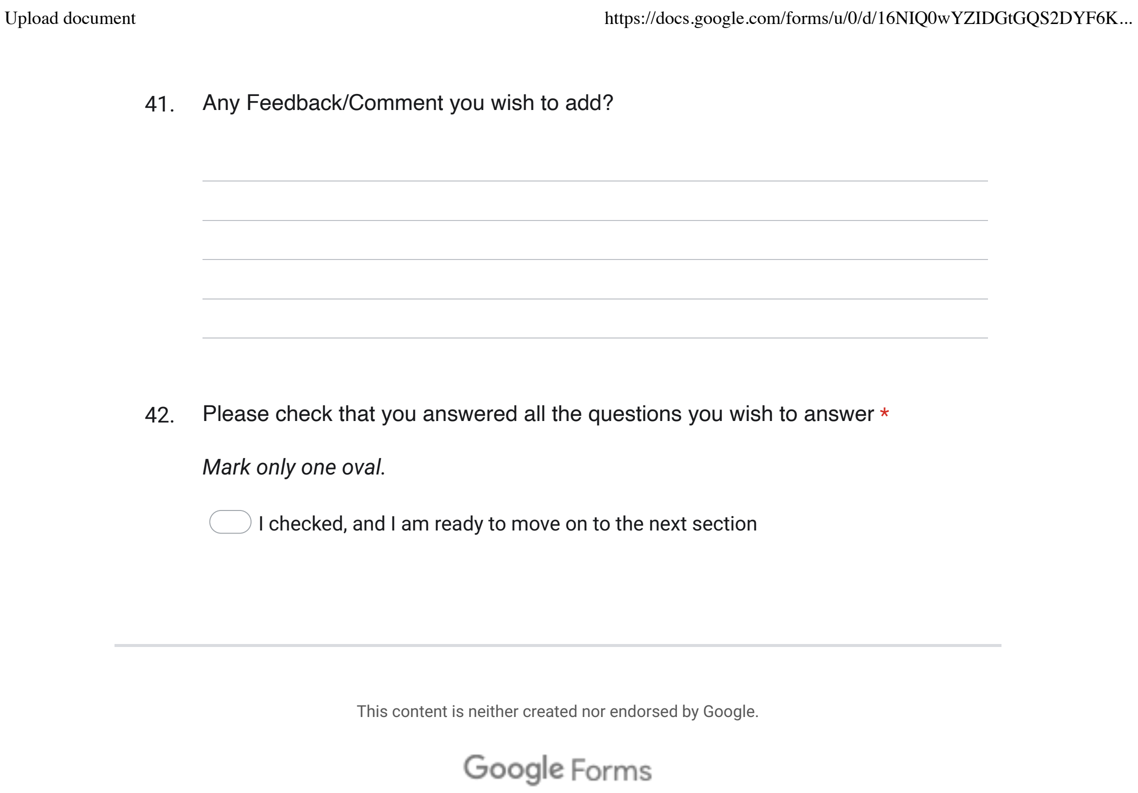
	1	2	3	
No	○	○	○	Yes

40. I feel like I just can’t stop playing

Mark only one oval.

	1	2	3	
No	○	○	○	Yes

C4. Qualitative Feedback



Upload document https://docs.google.com/forms/u/0/d/16NIQ0wYZIDGtGQS2DYF6K...

41. Any Feedback/Comment you wish to add?

42. Please check that you answered all the questions you wish to answer *

Mark only one oval.

○ I checked, and I am ready to move on to the next section