Behavioural and Neurophysiological Measures of Haptic Feedback during a Drilling Simulation

by

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An oral defense of this thesis took place on August 14, 2019 in front of the following examining committee:

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Chair of Examining Committee	Dr. JoAnne Arcand
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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

Virtual environments (VEs) and computer-generated simulations are becoming more prevalent as tools for education, rehabilitation, and training purposes. As technology enhances the quality and quantity of human-machine interfaces, it is essential that we expand our understanding of multimodal interactions, and how they influence our virtual experience and associated brain activity. Haptic sensation, or touch, is often neglected in VE research. In this thesis, Study 1 showed that haptic force-feedback in a drilling simulation improved motor performance and ratings of perceived reality, as compared to trials without haptic feedback. Study 2 used electroencephalography measures and demonstrated greater desynchronization in trials with haptic feedback, as compared to trials without haptic feedback. Large effect sizes were found between haptic and non-haptic trials in the alpha frequency band (8-13 Hz). This work provides evidence that task-relevant haptic feedback can enhance motor performance, and may facilitate motor learning processes.

Keywords: haptic feedback; simulation; motor performance; electroencephalography; event-related desynchronization.

DECLARATION

The work presented in this thesis consists of original work of which I have authored, except where acknowledged in the text. I hereby declare that the materials contained within this thesis have not been previously submitted, either in part or in whole, for a degree at this or any other institution. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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The research work in this thesis was performed in compliance with the regulations of Ontario Tech's Research Ethics Board under #1504.

____________________________________ Brianna Grant

STATEMENT OF CONTRIBUTIONS

The work described in Chapter 3 and 4 was performed using a Novint Falcon provided by the Gamer Lab operated by Dr. Bill Kapralos. The drilling simulation, created using the Unity game engine by Unity Technologies, was developed by student collaborators in the Faculty of Business Information and Technology, under Dr. Kapralos' and Dr. Alvaro Uribe-Quevedo's supervision. I was responsible for operating the simulation, and collecting and analyzing all the data that was recorded during the experiments.

The data analysis described in Chapter 4 used a custom MATLAB code, written and provided by Dr. Imran Niazi, a Senior Research Fellow at the New Zealand College of Chiropractic, in Auckland, New Zealand. I was responsible for collecting and analyzing electrophysiological data for all experiments.

I hereby certify that I am the sole author of this thesis and no part of this thesis has been published or submitted for publication. I have used standard referencing practices to acknowledge ideas, research techniques, or other materials that belong to others. Furthermore, I hereby certify that I am the sole source of the creative works and/or inventive knowledge described in this thesis.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
CNS	Central nervous system
DLPFC	Dorsolateral prefrontal cortex
EEG	Electroencephalography
ERD	Event-related desynchronization
ERS	Event-related synchronization
ISE	Immersive simulated environment
M1	Primary motor cortex
MANOVA	Multivariate analysis of variance
PFC	Prefrontal cortex
PPC	Posterior parietal cortex
S1	Primary somatosensory cortex
S2	Secondary somatosensory cortex
VE	Virtual environment
VR	Virtual reality

LIST OF FIGURES

INTRODUCTION TO THE THESIS

Virtual reality (VR) and immersive simulated environments (ISEs) are increasingly popular tools for education and training, especially in occupational settings, which include rehabilitation, surgical training, military personnel, and first-responders (Coles, Meglan, & John, 2011; Cox et al., 2010; Deutsch, 2009; Farra, 2015; Williams-Bell, Kapralos, Hogue, Murphy, & Weckman, 2015). Simulating adverse environments and complex tasks is now feasible and affordable with the use of VR and ISEs. Graphic rendering in VR simulations has been studied extensively, while there is an apparent lack of information regarding the other senses (Kapralos, Collins, & Uribe-Quevedo, 2017). The sense of touch is often overlooked in ISE applications, while high-fidelity (accurate) visual displays are becoming increasingly commonplace. Simulating the touch sensation falls under the term of haptics, which typically refers to human-machine touch interactions (Culbertson, Schorr, & Okamura, 2018; Srinivasan, 2016). Haptic devices can provide users with touch and kinesthetic feedback while manipulating a virtual or real object. Force feedback (provided by graspable devices) and cutaneous feedback (offered by wearable or touchable devices) can deliver effective haptic sensation during tasks in virtual environments, even when delivered by low-fidelity devices (Culbertson et al., 2018; Melaisi, Rojas, Kapralos, Uribe-Quevedo, & Collins, 2018). Fidelity is defined as the degree of precision with which the virtual element represents the real-world: high-fidelity devices are generally more expensive, as more time is needed to ensure accurate levels of feedback (Andrews, Carroll, & Bell, 1995; Coles et al., 2011). However, research is still needed to assess if feedback provided by high-fidelity ISEs results in enhanced task performance and motor learning, or if lower-fidelity devices can successfully provide this enhanced learning.

Two major types of fidelity exist in the training simulation world – physical and functional (Andrews et al., 1995). Physical fidelity refers to the environmental and task layout of the simulated environment (Andrews et al., 1995). Strong physical fidelity would include accurate visual presentations that the user would expect to see in the real world. Functional fidelity denotes the way that the simulation functions, or how well the equipment performs compared to its real-world mechanisms (Andrews et al., 1995). Functional fidelity is related to the presentation of the task stimulus and how the user responds. High-fidelity devices can provide more accurate tactile sensations, which may enhance user experience and task performance (Coles, John, Gould, & Caldwell, 2009). These devices are often costly and inaccessible to the consumer (Culbertson et al., 2018), therefore it is necessary to assess the quality of low-end haptic devices, and examine their influence on perception, task performance and associated brain activity in virtual environments (VEs).

User experience is an essential aspect in effective design of immersive environments, and subjective presence is often assessed to examine the immersive qualities of the technology used to create the virtual world. Presence refers to the feeling of being in the simulated environment, regardless of the user’s actual location and surroundings (Wirth et al., 2007; Witmer & Singer, 1998). Computer graphics technology has greatly enhanced visual immersion by providing realistic rendering of computer-generated worlds (Flavián, Ibáñez-Sánchez, & Orús, 2019), ultimately resulting in more immersive experiences (Baumgartner, Valko, Esslen, & Jäncke, 2006; Kober, Kurzmann, & Neuper, 2012; Kroupi, Hanhart, Lee, Rerabek, & Ebrahimi, 2016). An important distinction between immersion and presence must be made clear – the degree of immersion is an objective property, describing the qualities of the system that provoke the user’s experience in the VE, while presence can be interpreted as the subjective response to the system (Sanchez-Vives & Slater, 2005). The way in which we perceive the virtual world depends on the quantity and quality of sensory information as well as the frame-rate and latency of the generated system (Sanchez-Vives & Slater, 2005). VEs typically focus on the quality of visual immersion, often neglecting the other senses. Simulating audio and haptic sensations is becoming more prevalent in VR research, demonstrating the importance of perceptual-based rendering (Ballas, 2007; Coles et al., 2009; Kapralos et al., 2017; Kerdegari, Kim, & Prescott, 2016; Melaisi et al., 2018). High-fidelity simulations generally induce greater presence experiences, however, an alternate view of presence reveals the role of supported actions in the VE as a fundamental component of the experience of reality (Sanchez-Vives & Slater, 2005). This idea complements the notion that movement and perception are tightly bound, and in order to move effectively in a VE, we must have accurate sensory information from the system.

Motor learning describes the behavioural and neurophysiological adaptations that occur following practice – often resulting in enhanced spatial and temporal accuracy of motor skills (Willingham, 1998). Sensorimotor processing, involving sensory information from the physical environment as well as from the individual’s musculoskeletal system, provides consistent updating of the body schema, and allows us to move and interact with the ever-changing world around us. The body schema is known as an unconscious spatial map of the body that keeps us aware of our posture and limb positions, allowing us to move effectively in an environment (Head & Holmes, 1911; Maravita & Iriki, 2004). The complexity of sensorimotor functioning demonstrates how movement and sensation are intrinsically linked – our motor outputs are guided by sensory inputs, and movement creates additional somatosensory information, updating our body schema and allowing us to execute goal-directed movements. Changes in motor behaviour are often measured as performance accuracy; alterations in movement errors as well as response time can signify the underlying plastic changes occurring in the brain (Boudreau, Farina, Oppenhagen, & Falla, 2010; Classen, Liepert, Wise, Hallett, & Cohen, 1998; Karni et al., 1995). Altered afferent input has been shown to induce cortical and subcortical changes, ultimately influencing motor behaviour (Dancey, Murphy, Andrew, & Yielder, 2016; Flor, Braun, Elbert, & Birbaumer, 1997; Murphy, Taylor, Wilson, Oliphant, & Mathers, 2003; Tinazzi et al., 1998).

As technology advances the quantity and quality of human-machine interactions , subsequently providing new combinations of sensory input, it is essential to explore which types of sensory feedback provide beneficial plasticity (e.g. motor learning, enhanced performance, etc.), and whether their absence may negatively influence these changes. Therefore, this research aims to examine the behavioural and perceptual effects of task-relevant haptic feedback, and to explore differences in brain activity during trials with and without haptic feedback.

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OBJECTIVES AND HYPOTHESES

Research Objectives

1. To examine the effects of task-relevant haptic feedback on motor performance and the subjective reality experience during a computer-based drilling simulation.
2. To explore differences in brain activation patterns during haptic and non-haptic trials of a drilling simulation.
3. To determine whether subjective ratings of reality are enhanced by haptic sensory information, and whether this corresponds to neural markers of effective immersion.

Research Hypotheses

1. Task-relevant haptic feedback will improve motor performance in a simulated drilling task. Trials with haptic feedback will elicit less errors than the trials without haptic feedback.
2. Haptic feedback trials will provide more somatosensory information to the user, therefore altering the patterns of brain activity. Specifically, more activity will be present in parietal regions in the haptic condition, compared to the non-haptic condition.
3. If haptic trials provide higher scores of reality, then neural correlates of immersion, similar to those found in spatial presence, will be found. Specifically, greater desynchronization in the alpha and beta frequency bands will be present in the haptic trials, at specific electrode locations over the scalp.

OVERVIEW

This thesis is divided into the following chapters:

1. Literature Review
2. Proposed Research
3. Manuscript 1
4. Manuscript 2
5. Thesis Summary
6. Appendices (including data tables, participant consent form, and questionnaires)

CHAPTER 1. LITERATURE REVIEW

1.1. INTRODUCTION TO THE LITERATURE REVIEW

This section is dedicated to review current literature relevant to the proposed research of this thesis. This includes the sensorimotor system and its neuroanatomy, receptors involved in the sensation of touch and proprioception, processes involved in motor learning, neural plasticity, and the use of virtual environments for training. The role of electroencephalography (EEG) techniques to analyze cortical spectral power changes, as well as neural correlates of presence, will also be discussed. The purpose of this literature review is to show where current scientific research stands regarding multimodal stimuli (i.e. audiohaptic) in immersive simulations, providing a basis for this thesis.

1.2. THE SENSORIMOTOR SYSTEM

The sensorimotor system is a complex neural network which involves gathering afferent information from the periphery, processing somatosensory inputs within the CNS, and stimulation of appropriate efferent pathways, resulting in the maintenance of posture and functional joint stability (Lundy-Ekman, 2013; Riemann & Lephart, 2002). Sensory information from the body enters the spinal cord through dorsal root ganglion cells, and is transmitted through various cortical and subcortical regions (Kandel, Schwartz, Jessell, Siegelbaum, & A.J., 2013). This system, called somatosensation, must be resilient and adaptable in order to update body awareness and movement coordination across a variety of tasks. Somatosensation includes interoception (mostly unconscious sensations of internal organs), exteroception (the direct interactions we have with the external world and how it impacts us; touch, thermal sensation, and pain), and proprioception (the sense of one’s own body, limb position, and posture), which are all mediated by dorsal root ganglion neurons (Kandel et al., 2013). These sensations are critical for carrying out tasks of daily life, including accurate movement plans. Cutaneous receptors within skin can interpret superficial sensory information to the CNS, such as touch (vibration and pressure), temperature changes, and pain (Lundy-Ekman, 2013). Proprioception describes the awareness of joint position signaled via receptors found within muscles and tendons, which provide sensory information during movement (Lundy-Ekman, 2013). The visual and vestibular systems are also fundamental in the coordination of movements, however, proprioceptors and peripheral mechanoreceptors are critical to providing haptic input during new skill acquisition. Given the focus of this thesis, this section will focus on the receptors responsible for touch and proprioception.

The hand is the most efficient organ of the human body for exploration of an environment, as the density of mechanoreceptors in the palm and fingers convey accurate spatial properties of surfaces and manipulated objects (Kaczmarek, Webster, Bach-y-Rita, & Tompkins, 1991). Mechanoreceptors respond to mechanical deformation by touch, pressure, or stretch, and can be found within cutaneous tissue, ligaments, joint capsules, and muscle tissue. Superficial receptors located within glabrous skin include Meissner's corpuscles, sensitive to light touch and vibration stimuli, and Merkel's cells, stimulated by pressure (Kaczmarek et al., 1991; Kandel et al., 2013). Subcutaneous receptors include Ruffini endings, responsive to stretching of the skin, and Pacinian corpuscles, which respond to touch and vibration (Kandel et al., 2013). It is unlikely that one type of receptor will respond to an external stimulus, rather, multiple receptors stimulated by a single tactile stimulus will initiate various action potentials to the CNS. All of these tactile receptors transmit sensory information via type Aβ (II) afferents (Lundy-Ekman, 2013). This array of receptors allows accurate discrimination between surfaces of objects, and gives rise to our interactions with the environment.

Receptors involved in proprioception are located within the muscles, tendons, and joint capsules. These specialized receptors convey important information regarding the state of the muscle, as well as limb position during movement. Muscle spindles, the encapsulated sensory receptors located within muscle tissue, consist of three main components: intrafusal muscle fibers with central non-contractile regions, afferent sensory endings that terminate on non-contractile areas of intrafusal fibers, and efferent motor neurons that terminate on lateral contractile areas of intrafusal fibers (Kandel et al., 2013). The spindle's main function is to signal changes in muscle length, relaying information about limb position to the CNS (Kandel et al., 2013). Changes in muscle length are comprised of two stages: a dynamic phase, during which the length of the fibers is changing; and the static phase, when the muscle has stabilized at a new length (Kandel et al., 2013). The spindle's sensory endings include both type Ia (primary) and type II (secondary) endings (Kandel et al., 2013). Primary endings are also known as annulospiral endings, as they wrap around non-contractile regions of intrafusal muscle fibers; whereas secondary endings are often called flower-spray endings, and are located adjacent to primary endings (Kandel et al., 2013). Both primary and secondary endings respond to the static, or steady-state phase of muscle stretching, while the dynamic phase stimulates discharge of only primary sensory endings (Kandel et al., 2013). To maintain the spindles' sensitivity during changes in muscle length from alpha motor neurons, gamma motor neurons become active, contracting (shortening) the ends of the intrafusal fibers (Kandel et al., 2013). Gamma motor neurons fire with alpha neurons, altering the mechanical properties of the intrafusal fibers in synchrony with extrafusal fibers (Kandel et al., 2013).

Golgi tendon organs, innervated by type Ib afferents, are imbedded within muscle tendons, and respond to changes in tension from both active and passive stretch of muscle tissue (Kandel et al., 2013). Ligament receptors, Ruffini endings, and Pacinian corpuscles respond to mechanical changes of the joint capsule (Kandel et al., 2013). Normal proprioception relies on accurate sensory information from muscle spindles, joint receptors, and cutaneous mechanoreceptors, working synchronously to update our body awareness and to execute goal-directed movements.

1.2.1. Neuroanatomy of Somatosensation

Although the type of sensory information may vary, the different receptors involved in somatosensation share similar neuroanatomical arrangements. Receptors transmit mechanical stimulation into electrical potentials, which are conducted along the distal axon branches of dorsal root ganglion neurons (Kandel et al., 2013). These peripheral axons are classified by axon diameter, from smallest to largest: C, Aδ, Aβ (II), Ib, Ia (Kandel et al., 2013). Cutaneous mechanoreceptors and proprioceptors are innervated by large-diameter myelinated axons, which rapidly transmit action potentials. First-order axons conduct the afferent information to the spinal cord or brainstem, representing the first synapse from the point of receptor stimulation (Kandel et al., 2013). Afferent signals ascend to various cortical and subcortical brain regions (i.e. the thalamus), where stimuli from multiple senses are integrated and processed, resulting in sensation (Lundy-Ekman, 2013). Sensation can be described as our *awareness* of sensory stimuli, which occurs once peripheral inputs are processed at cortical and subcortical regions of the brain (Lundy-Ekman, 2013). Perceiving spatial properties of objects in contact with the skin, a fundamental aspect of our ability to interact with the environment, also occurs after the stimulus is recognized by the CNS.

The final synapse into third-order axons relay sensory information that is somatotopically organized in the cortex, revealing ‘sensory maps’, or representations of specific areas of the body (Kandel et al., 2013). Information from sensory receptors is conveyed through the ascending pathway, through the thalamus, and terminating at the primary somatosensory cortex, located at the postcentral gyrus (Kandel et al., 2013). Sensory inputs activate pathways that lead to sensation of the stimulus and activation of motor planning programs.

The primary somatosensory area of the cerebral cortex (S1), the secondary somatosensory cortex (S2), and the posterior parietal cortex (PPC) are cortical structures involved in conscious perception of discriminatory touch and proprioception (Kandel et al., 2013). Tactile and proprioceptive information arising from cell bodies in the dorsal root ganglion ascends through the dorsal column of the spinal cord (Kandel et al., 2013). Axons arising from the lower limb are located medially, in the fasciculus gracilis, while axons from the upper limb are added laterally, occupying the fasciculus cuneatus (Kandel et al., 2013). Both types of axons ascend to the medulla, where they synapse with second-order neurons of the nucleus gracilis and nucleus cuneatus, respectively (Kandel et al., 2013). Axons from second-order neurons cross over (decussate) as the internal arcuate fibers, and continue to the thalamus as the medial lemniscus (Kandel et al., 2013). These axons synapse with third-order thalamocortical neurons, which convey information to the primary somatosensory area of the cerebral cortex (Kandel et al., 2013).

Neurons in S1 identify the location of the stimuli, and discriminates the shape, size, and texture of objects (Lundy-Ekman, 2013). Sensory association areas (S2 and PPC) analyze sensory inputs received from S1 and the thalamus (Kandel et al., 2013). Neurons in these association areas integrate tactile and proprioceptive input from manipulation of an object, and can recognize sensations by comparing information from the novel object to memories of other objects (Kandel et al., 2013). The PPC is composed of superior and inferior parietal lobules, and is responsible for high-order functions, such as sensory integration, spatial perception, visuomotor control, and directing attention (Wolpert, Goodbody, & Husain, 1998). This association area integrates relevant sensory information to guide voluntary movement and attention (Wolpert et al., 1998). Constructing a spatial representation of one’s own body occurs in the parietotemporal association area, which has important implications for body schema and movement planning (Lundy-Ekman, 2013; Wolpert et al., 1998). Body schema can be interpreted as an action-oriented spatial body map in the brain, utilizing proprioceptive, tactile, and visual inputs to localize objects in our extrapersonal space, as well as keeping a constantly updated status of limb position and posture (Head & Holmes, 1911; Maravita & Iriki, 2004). The parietal lobe is thought to be a significant contributor to the egocentric point of view (Kandel et al., 2013; Vallar et al., 1999), which is also the viewpoint in many gaming and VR simulations (Baumgartner et al., 2008; Baumgartner et al., 2006; Kober et al., 2012; Kober & Neuper, 2012; Williams-Bell et al., 2015). The PPC has extensive connections to the dorsolateral prefrontal cortex (DLPFC), which gives rise to our sense of self-awareness and the planning of goal-directed behaviour (Lundy-Ekman, 2013).

The complex nature of sensorimotor function demonstrates how motor control and sensation are tightly bound - motor output is guided by sensory input, and movement subsequently updates the system with new sensory information. This system is constantly updating our body schema, and is fundamental to our perception of the environment, and to the execution of goal-directed movements.

1.2.2. Neuroanatomy of the Voluntary Motor Pathway

The primary motor area (M1), located at the precentral gyrus of the cerebral cortex, is arranged somatotopically, in a similar fashion to S1 (Kandel et al., 2013). Certain regions of M1 correlate to activity in specific muscle groups; the more we engage and strengthen a motor pathway (through repetition, motor training, etc.), the greater the cortical area dedicated to that function (Kandel et al., 2013). M1 is the source of the majority of corticospinal neurons, and is responsible for controlling voluntary movements (Lundy-Ekman, 2013). Much of this cortical area is dedicated to fine movements of the face and hand (Kandel et al., 2013).

Fibers of the lateral corticospinal tract descend through the internal capsule, cerebral peduncles, anterior pons, and form the medullary pyramids, where neurons cross over to the contralateral side (Kandel et al., 2013). Information descends through the lateral column, eventually synapsing with alpha and gamma lower motor neurons in the ventral horn of the spinal cord (Lundy-Ekman, 2013). Motor planning areas, consisting of premotor and supplementary motor regions, are important contributors to the voluntary control of movement. The premotor area controls the trunk and girdle muscles, stabilizing the joints in preparation of movement and postural adjustments, while the supplementary motor area coordinates the initiation of movement, head orientation, and bimanual movements (Lundy-Ekman, 2013). These three areas are anatomically connected, and it is important to note that the control of movement is mediated by outputs of both M1 and motor planning areas (Kandel et al., 2013).

Motor information conveyed through the corticospinal tract is modified by somatosensory information and other motor regions of the brain (Kandel et al., 2013). The sensorimotor system constantly updates available information from proprioceptive, haptic, and visual inputs in order to execute accurate motor commands.

1.3. MOTOR SKILL ACQUISITION AND LEARNING

Sensory information from both the external environment and the individual's musculoskeletal system allows us to move effectively, and movement allows us to interact with the world around us. This sensorimotor feedback loop is essential for adapting to a changing environment and learning through haptic (touch) experience. Motor activity can be classified as either fine or gross; requiring small muscle groups to perform precise tasks, or large muscle groups to perform generalized movements, respectively. Repetition of novel skills with extrinsic feedback is an effective way to develop and retain motor skill behaviours (Van Vliet & Wulf, 2006). Motor learning describes the enhanced temporal and spatial accuracy of motor skills that results from practice (Willingham, 1998). Intrinsic feedback is any sensory or perceptual information acquired through movement (somatosensation), while extrinsic feedback is provided by an external source. While intrinsic feedback aids in formulating an internal representation of movement, extrinsic feedback is generally more effective for motor learning, as it can be presented to the performer via auditory cues (from an instructor), or visual cues (from a display/monitor). Extrinsic feedback can be categorized as either knowledge of results (KR), or knowledge of performance (KP) (Magill, 2011). In terms of experimental paradigms, motor skill performance can be measured in terms of reaction time or number of errors (accuracy). Enhanced motor performance after a training period demonstrates the plastic nature of the human brain (Classen et al., 1998).

1.3.1. Neural Plasticity

Neural plasticity refers to any enduring change in the properties of the CNS that develop throughout our lives. These changes may be mediated by strengthened internal connections, reorganization of representation patterns, or by structural and functional changes of neurons (Boudreau, Farina, & Falla, 2010; Sanes & Donoghue, 2000). Numerous studies have shown the association of altered motor behaviour and neuroplastic changes, such as the changes following novel motor skill acquisition (Boudreau, Farina, Oppenhagen, et al., 2010; Classen et al., 1998; Karni et al., 1995; Kleim et al., 2002), or those associated with acute or chronic pain (Baarbé, Yielder, Haavik, Holmes, & Murphy, 2018; Dancey et al., 2016; Flor et al., 1997). Adaptive neural changes are those associated with behavioural advantages, such as enhanced motor performance after a period of motor training. Maladaptive plasticity refers to the occurrence of unfavourable behaviours, such as decreased motor performance in the presence of experimental (acute) pain. Prior research reveals the occurrence of maladaptive plastic changes in the form of repetitive strain injuries, causing decreased motor output and degraded hand representation in the primary somatosensory cortex of primates (Byl et al., 1997). Conversely, enlarged cortical representation of the left fingers have been found in string instrument players, while their right hand representation appeared normal (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995). This suggests that repetitive practice of motor skills can enhance motor performance, and this change in performance may be due to the underlying neural changes associated with plasticity.

Numerous studies have observed the adaptability of the sensorimotor system in response to altered afferent input (Classen et al., 1998; Dancey et al., 2016; Murphy et al., 2003; Tinazzi et al., 1998). Flor and colleagues (1997) found that patients with chronic low back pain possess an altered cortical representation of the low back, located in S1. These changes were site-specific, localized only to the region of pain (Flor et al., 1997). These findings coincide with phantom limb studies, which demonstrate the correlation between the shift in representation of an amputated limb and the severity of pain perceived by amputees (Flor et al., 1995; Flor et al., 1998). These findings suggest that altered afferent input can induce cortical and spinal plastic changes, resulting from patterns of altered behaviour. As advancing technology enhances both the quality and quantity of sensory information while interacting with multimedia (Frauenberger, Putz, & Holdrich, 2004), ultimately providing alterations of sensory input, it is critical to explore which types of sensory feedback are critical for beneficial plasticity and whether their absence may predispose users to maladaptive plasticity.

1.4. PERCEPTION IN IMMERSIVE SIMULATED ENVIRONMENTS

As multimedia and virtual environments gain popularity in entertainment and education fields (Dickey, 2005), we have an increasing need to expand our understanding of human perceptual systems and how they are influenced in simulated worlds. The success of immersive simulated environments (ISEs) is dependent on the user's perception of their surroundings and how real the task seems. The reproducibility of human senses, mainly vision, sound, and touch, is fundamental to immersing the user into the virtual experience. Our perceptual system does not necessarily rely on individual sensory inputs, but rather a multimodal array of information with complex interactions. In a real environment, our senses gather information from external stimuli in our physical surroundings to be organized and interpreted through the process of multisensory integration (Seitz, Kim, van Wassenhove, & Shams, 2007). Different senses can interact with one another, influencing this integration process and altering our perception of the world. For instance, the visual dominance effect is a phenomenon where participants fail to respond to the auditory component of an audiovisual stimulus more often than they fail to respond to the visual input (Colavita & Weisberg, 1979). This dominance of vision has even been shown to persist with visuotactile bimodal stimuli (Hartcher-O'Brien, Gallace, Krings, Koppen, & Spence, 2008). Other research has shown that the addition of auditory stimuli can influence our perception of a visual stimulus. For instance, contextual (task-relevant) sound effects can allow slow animations to be perceived as smoother than fast animations, which can have important implications for designing immersive simulations without increasing computational requirements (Hulusić, Debattista, Aggarwal, & Chalmers, 2011; Mastoropoulou, Debattista, Chalmers, & Troscianko, 2005).

The way we interpret our environment and our ability to interact with that environment is determined by the way our senses integrate (Harris et al., 2015; Kapralos et al., 2017; Seitz et al., 2007). Our awareness of joint position allows us to coordinate and execute accurate movements, and contributes to the organization of the body schema. Body schema is an internal spatial map of the body, which requires regular updating from the somatosensory system to maintain accuracy of the map (Maravita & Iriki, 2004). The body schema is incredibly adaptable, demonstrating plastic qualities when exposed to altered afferent input; such is the case when a tool becomes an extension of the hand after a period of tool-use training (Iriki, Tanaka, & Iwamura, 1996; Maravita, Spence, & Driver, 2003). Peripersonal space describes the area near an individual, where visual receptive fields are mainly located (Fogassi et al., 1996). Peripersonal space and sensory receptive fields can be extended upon repeated tool use (Fogassi et al., 1996; Maravita, Clarke, Husain, & Driver, 2002; Maravita & Iriki, 2004). It is imperative that we understand how different sensory stimuli can influence our perception of an environment, especially when employing these stimuli in virtual worlds for the purpose of behavioural and motor training.

1.4.1. The Presence Experience

The effectiveness of ISEs and VEs partially relies on the sense of presence that the user experiences, since it is likely that greater levels of presence will induce behaviour that is appropriate for the task (Sanchez-Vives & Slater, 2005; Slater, 2004; Slater, Linakis, Usoh, & Kooper, 1996). When considering the use of VEs for training, the generated environment should replicate the actual environment as closely as possible, so the learned behaviour can be transferred to real-world scenarios. Spatial presence in VEs is often defined as the subjective experience of “being there” within the VE, regardless of the actual location of the user (Witmer & Singer, 1998). Measuring presence in task simulations can help to improve the design of virtual worlds for entertainment, rehabilitation, and training purposes. Factors that influence an individual’s presence experience include external sensory stimuli from the task or environment, and internal attention and motivation. The presence experience is a product of the spatial-functional representation of the VE, and is inherently different than the concept of immersion, which refers to the types and fidelity of the sensory inputs used to generate the VE (Schubert, Friedmann, & Regenbrecht, 2001; Slater et al., 1996).

Our perception of reality relies on sensory information from the environment around us, including the sensory feedback generated by the actions we produce. Immersive environments allow users to view or manipulate objects from various perspectives, an advantage that results in an opportunity for “learning by doing” (Dede, 1995; Dickey, 2005). The affordances offered in a virtual environment drive our interactions (Dickey, 2005), therefore, presence can also be noted as the support of action within the environment (Slater, 2004). It is also thought that proprioceptive and sensory inputs should closely match for an enhanced presence experience (Slater, Usoh, & Steed, 1995).

Several external factors can be manipulated to create an enhanced presence experience which can greatly impact the user’s perception of the VE, and altering the media itself is only one small detail (Baumgartner et al., 2008; Kroupi et al., 2016; Witmer & Singer, 1998). Baumgartner and colleagues (2008) were able to create two separate experiences of a non-interactive roller coaster simulation: the first established very low feelings of presence, incorporating horizontal turns, while the second simulation implemented exciting vertical twists and loops, inducing higher ratings of presence. Media quality (i.e. high vs. low) seems to be more important in generating greater levels of presence, when compared to how the media is displayed (i.e. 2-dimensional vs. 3-dimensional) (Kroupi et al., 2016). The ability to interact within an immersive virtual environment typically enhances a user’s sense of presence (Witmer & Singer, 1998). Passive, non-interactive simulations may lack the interactive component that is necessary for practicing motor skills, which is a critical component of motor learning adaptations (Levin, Weiss, & Keshner, 2015).

1.4.2. Haptic Sensations in ISEs

Over the past two decades, computer graphics rendering has greatly improved the visual aspects of virtual simulations, resulting in enhanced immersive experiences. Developers of ISEs generally aim to produce faithful representations of real environments, especially when designing simulations for education and training. These applications strive to produce high levels of fidelity, which describes the extent to which a simulation is perceived as real (Andrews et al., 1995). Visual fidelity is most often the focus of enhancements to the virtual experience, although recent work has highlighted the importance of auditory stimuli on perceived ratings of fidelity (Kapralos et al., 2017; Lipscomb & Zehnder, 2004; Melaisi et al., 2018). In recent years, an emphasis on simulating the touch sensation has emerged, likely due to the rise of complex human-machine interactions (Culbertson et al., 2018). Haptic perception is characterized by information acquisition from both kinesthetic and tactile stimuli, provided through active exploration of our environment (Culbertson et al., 2018; Srinivasan, 2016). Without haptic sensation, we would have great difficulty grasping and manipulating objects, recognizing different surface textures, and performing accurate movements with tools.

Lower-end haptic devices are widely available to the consumer, and are relatively inexpensive, however, they typically cannot generate high levels of force-feedback, resolution, or refresh rate (Melaisi et al., 2018). The application of low-fidelity haptic devices is mainly restricted to simple vibrations and small amounts of force-feedback, employed by different motors and actuators (Melaisi et al., 2018). They are currently utilized in devices such as video-game controllers, portable gaming consoles, haptic gloves and vests, and in mobile phones. Devices with high levels of haptic fidelity can be costly and inaccessible to the consumer, and are often utilized in tasks requiring precision, such as robot teleoperations and surgical simulations (Culbertson et al., 2018). Research has demonstrated the importance of ISEs in the medical field, allowing student practitioners to perform on virtual patients, with haptic feedback providing vital sensory information about the state of tissues and organs (Basdogan et al., 2004; Coles et al., 2009).

Lower-end devices are still effective in entertainment and education-based applications, and they may also have the ability to enhance user experience in training-based simulations, leading to improvements in motor performance (Coles et al., 2011; Culbertson et al., 2018). It is important to examine how low-end devices can influence the user's perceptual system and motor learning processes, in order to understand which types of training simulations require the increased fidelity provided by high-end devices, and which simulations are equally effective with lower-end consumer devices.

1.4.3. Virtual Environments for Training

Virtual environments are being adopted into occupational settings as a means of education and training (Cox et al., 2010; Gamberini, Chittaro, Spagnolli, & Carlesso, 2015; Williams-Bell et al., 2015). In order for the simulation to represent real-world scenarios, the user must feel as though the tasks presented in the simulation are real – this is typically done by inducing a strong presence experience or by replicating the types of sensory stimuli they would experience in the actual task. These characteristics can be achieved by manipulating the quality of the media (i.e. visual fidelity) and subjecting the user to realistic stimuli, respectively. In complex training scenarios, users are required to make rapid decisions, often requiring sensory interpretation followed by accurate execution of motor skills.

Gamberini and colleagues (2015) explored behavioural responses of participants in an emergency scenario in VR. Participants were instructed to reach the safety location in the fastest time possible when presented with a sudden fire. Researchers implemented aspects of safety training within the VE by allowing participants to choose to help someone requiring assistance, or continue to the safety destination. Results demonstrated that subjective levels of anxiety increased when forced with the life-saving decision, suggesting an enhanced presence experience (Gamberini et al., 2015).

First responders provide an interesting cohort for VR research, as they receive constant exposure to emergency conditions on a regular basis. They are often challenged with cognitively complex situations, requiring immediate decisions motor responses. Bailie and colleagues (2016) explored the use of an ISE, incorporating visual and auditory stimuli to replicate a burning building, in order to train firefighters on team coordination and spatial awareness. They found that an augmented VR simulation was more practical in terms of cost and safety than standard training, which typically occurs off-location at specially designed facilities (Bailie, Martin, Aman, Brill, & Herman, 2016).

There is still much to examine when considering the implementation of VR as a training modality, such as the translation of learned behaviour to the real world (Farra, 2015). Training with VR technology is a safer alternative to exposure in adverse climates or life-threatening situations, and it is essential that we expand our understanding on skill retention in real-world environments. Neurophysiological techniques can be utilized to compare changes in brain activation in simulated VEs and the actual environment, which will help to further develop an understanding of underlying cognitive processes involved in the perception of ISEs. Ultimately, this may allow us to identify neural signatures, or neural correlates, of a “trained” brain state. This would permit researchers to systematically investigate whether the modality and fidelity of sensory feedback can alter brain activation to be more similar to the activity observed in the real world.

1.5. ELECTROENCEPHALOGRAPHY

The most common methods of monitoring neurological activity within VR environments include electroencephalography (EEG) and functional magnetic resonance imaging (fMRI). Some companies with EEG technology have created portable options, allowing participants to sit or stand comfortably throughout studies (Jaiswal, Ray, & Slobounov, 2010; Ninaus, 2014). This is especially convenient in ISE research, as participants can interactively navigate throughout an environment while researchers collect behavioural data. This technique is cost-effective compared to fMRI, with an exceptionally high temporal resolution that can directly measure cortical activity to the millisecond (Ninaus, 2014).

EEG is a non-invasive technique which measures post-synaptic cortical activity of numerous pyramidal neurons recorded from electrodes near the scalp (Nunez & Srinivasan, 2006). Sensory stimuli evoke transient time-locked changes of neural responses within the EEG – these changes are termed event-related potentials (ERPs) (Pfurtscheller & Lopes da Silva, 1999). ERPs demonstrate frequency-specific changes of neural activity, representing either increases or decreases in power within a given frequency band (Pfurtscheller & Lopes da Silva, 1999). These alterations may be due to an increase or decrease in synchrony of underlying neural tissue (Pfurtscheller & Lopes da Silva, 1999). Averaging and frequency analysis techniques are commonly used to detect and quantify these oscillatory changes. A decrease in neural synchrony is referred to as event-related desynchronization (ERD), while an increase in synchrony is event-related synchronization (ERS). These phenomena are generated by changes that control neural network oscillations (Pfurtscheller & Lopes da Silva, 1999). Two major factors influence the properties of EEG oscillations: intrinsic neuron membrane properties and the efficiency of synaptic processes, and the strength and extent of neural connectivity formed by various feedback loops (Lopes da Silva, 1991; Singer, 1993). The frequency of brain oscillations is negatively correlated with their amplitude – where increasing frequency demonstrates decreasing oscillatory amplitude (Pfurtscheller & Lopes da Silva, 1999). Since the amplitude of oscillations is proportional to the amount of synchronously active neurons, low frequencies (slow oscillations) consist of more neural elements than higher frequencies (Pfurtscheller & Lopes da Silva, 1999; Singer, 1993). Thus, it is essential to specify the frequency band of interest when quantifying changes in oscillatory power.

VR research often integrates EEG frequency analysis with subjective presence experience (Baumgartner et al., 2008; Baumgartner et al., 2006; Diemer, Alpers, Peperkorn, Shiban, & Mühlberger, 2015; Kober et al., 2012; Kroupi, Hanhart, Lee, Rerabek, & Ebrahimi, 2014; Kroupi et al., 2016). Correlation analysis determines how patterns of brain activation may influence the experience of presence. Research suggests that participants exposed to more immersive VR conditions will state higher ratings of presence, accompanied by strong activation in the parietal cortex, indicated by increased ERD within the alpha band (Baumgartner et al., 2006; Kober et al., 2012).

1.5.1. Event-Related Desynchronization and Synchronization

A basic element of measuring ERD/ERS is the EEG power post-stimulus, displayed relative to the baseline power (Pfurtscheller & Lopes da Silva, 1999). This is typically conveyed as a percentage change. ERD phenomenon is only meaningful if baseline activity (measured a few seconds pre-stimulus) illustrates rhythmicity, seen as a peak in the power spectrum (Pfurtscheller & Lopes da Silva, 1999). ERS is meaningful if the stimulus causes an appearance of rhythmic activity and a spectral peak, where it was not initially observed during baseline (Pfurtscheller & Lopes da Silva, 1999). The baseline period should be recorded several seconds prior to the onset of the stimulus, especially when alpha band frequencies are of interest (Pfurtscheller & Lopes da Silva, 1999).

The following calculation denotes the change in frequency band power (Pfurtscheller & Lopes da Silva, 1999):

$$\text{ERD/ERS \%} = \frac{(\text{average active power} - \text{average baseline power})}{(\text{average baseline power})} \text{ X } 100$$

Note that negative values indicate a relative decrease in power (ERD) and positive values indicate a relative power increase (ERS). Since event-related changes within the EEG need sufficient time to develop and recover, the epochs chosen for baseline and active power are critical for interpreting results. Averaged baseline power should be measured several seconds before movement-onset in motor tasks, as this desynchronization begins a few seconds before the initiation of movement. ERD induced by voluntary movements occur near sensorimotor areas of the cortex (Pfurtscheller & Lopes da Silva, 1999).

ERD can be interpreted as a correlate of cortical activity involved in the processing of sensory information or execution of movement (Pfurtscheller & Aranibar, 1979; Pfurtscheller & Lopes da Silva, 1999). Enhanced desynchronization is thought to be a result of a larger neural network involved in sensorimotor processing (Pfurtscheller & Lopes da Silva, 1999).

1.5.2. Frequency Bands of Interest

VR research utilizing neurophysiology methods typically observes changes within specific frequency bands. Theta (4-8 Hz), alpha (8-13 Hz), and beta (13-30 Hz) brainwaves have all been examined in ISE research (Baumgartner et al., 2006; Kober et al., 2012; Kroupi et al., 2016; C.-L. Lin, Shaw, Young, Lin, & Jung, 2012). Alpha wave desynchronization can be seen in two separate patterns, often divided into lower alpha frequencies (7-10 Hz) and higher alpha frequencies (10-12 Hz) (Pfurtscheller & Lopes da Silva, 1999). Low alpha desynchronization is observed over a widespread cortical area in response to a variety of tasks, and is thought to reflect processes of attention and general task demands (Pfurtscheller & Lopes da Silva, 1999). Conversely, upper alpha (also known as mu rhythm) desynchronization is topographically restricted, generally occurring in parietotemporal areas during the processing of sensory information (Pfurtscheller & Lopes da Silva, 1999). Similarly, beta waves are often subdivided into low beta (13-20 Hz) and high beta (21-30 Hz) (Kroupi et al., 2016).

Changes in the alpha band frequency have been shown to indicate cortical activation or deactivation within the frontal and parietal lobes (Baumgartner et al., 2006; Laufs et al., 2003). ERD near sensorimotor areas in the upper alpha and lower beta bands occurs approximately two seconds prior to voluntary movement (Pfurtscheller & Aranibar, 1979). This desynchronization occurs near the contralateral motor area several seconds before movement-onset, and becomes bilaterally symmetrical just prior to movement (Pfurtscheller & Lopes da Silva, 1999). This time-sensitive desynchronization occurs whether voluntary movements are fast and preprogrammed, or slow and dependent on sensory feedback from proprioceptive afferents (Pfurtscheller & Lopes da Silva, 1999). Contralateral mu ERD occurring before onset of movement seems to reflect general neural priming in sensorimotor areas, as similar desynchronization patterns can be found across movements of the thumb, finger, and hand (Pfurtscheller & Lopes da Silva, 1999). Mu ERD is mainly generated at the post-central gyrus, while the central beta (20-24 Hz) ERD is located more anteriorly, near the motor area (Pfurtscheller & Lopes da Silva, 1999).

Gamma frequency (36-40 Hz) synchronization on the contralateral side has been found in movement tasks, and may be related to sensorimotor integration (Pfurtscheller, Neuper, & Kalcher, 1993). These oscillations occur just before movement-onset and continue through movement execution. Gamma ERS signifies active information processing, and typically occurs at the same time as alpha band ERD (Pfurtscheller & Lopes da Silva, 1999). This would likely occur near the C3 electrode location.

Cortical theta band activity has been suggested to be involved in learning, spatial navigation, and sensorimotor integration (Cruikshank, Singhal, Hueppelsheuser, & Caplan, 2012). Theta and alpha wave bands are similar in frequency (4-8 Hz and 8-12 Hz, respectively), and are suspected to be closely related during the process of sensorimotor integration (Cruikshank et al., 2012). Several studies have found rhythmic activity occurring over the frontal midline region of the EEG during numerous tasks, such as spatial orientation and sensorimotor integration (Caplan, Madsen, Raghavachari, & Kahana, 2001; Caplan et al., 2003). Theta oscillations are also thought to influence long-term potentiation, a theorized mechanism of synaptic plasticity (Caplan et al., 2001). Similar to gamma frequencies, theta ERS has been observed during mu desynchronization.

1.5.3. Brain Regions of Interest

Two regions of the cerebral cortex that are suggested to be related to the presence experience include the frontal and the parietal lobes (Baumgartner et al., 2008; Baumgartner et al., 2006; Clemente et al., 2013; Jäncke, Cheetham, & Baumgartner, 2009; Kober et al., 2012; Kober & Neuper, 2012; Wirth et al., 2007). The frontal lobe is largely related to short-term memory and the planning of movements, while the parietal lobe is mainly concerned with somatosensory processing and the formulation of the body schema as it relates to extrapersonal space (Kandel et al., 2013). The parietal lobe is also involved in visual processing, responsible for assessing the shape and size of visual stimuli, whether from memory or from a novel stimulus (Wolpert et al., 1998). Constructing a spatial representation of one’s own body occurs in the parietotemporal area, which has important implications for movement planning (Wolpert et al., 1998). This brain region is also involved in attentional processes, with substantial neural connections to the frontal lobe for controlling movements related to directing attention (Wolpert et al., 1998). Two types of attention networks exist: the dorsal attention system, involved in voluntary goal-directed attention, and the ventral system, involved in the involuntary attention of unexpected stimuli (Vossel, Geng, & Fink, 2014). The dorsal network consists of the intraparietal sulcus and the frontal eye fields; this system involves maintaining spatial attention, saccade planning, and visual working memory (Vossel et al., 2014). Conversely, the ventral network consists of the temporoparietal junction and the ventral frontal cortex, responding when relevant stimuli appear outside the focus of spatial attention (Vossel et al., 2014).

Definitions of spatial presence include the idea that VEs can stimulate various sensory channels simultaneously, effectively engaging multiple components of the sensorimotor system (Biocca, 1997). Engagement of sensory systems enhances the user’s feelings of embodiment, or the feeling of being located within the mediated environment (Wirth et al., 2007). Spatial presence is often enhanced by media-generated stimuli, such as different forms of visual, auditory, proprioceptive, and haptic inputs (Wirth et al., 2007). Sensory presence relates to the user’s perception of the mediated environment as they would perceive the real world, and can be divided into auditory, visual, and haptic perception (Clemente et al., 2013). Jäncke and colleagues (2009) suggested a distributed network that is activated with the presence experience, and consists of dorsal and ventral visual streams, the parietal cortex, the premotor cortex, the mesial temporal areas, the brainstem, and the thalamus. Activity in the parietal cortex is thought to be associated with the egocentric spatial experience induced by virtual worlds (Baumgartner et al., 2008), whereas less activation of the dorsolateral prefrontal cortex (DLPFC) correlates to more intense feelings of presence (Jäncke et al., 2009).

The posterior parietal lobe is thought to be responsible for visuospatial organization, as those suffering from spatial neglect often have lesions over this area, with the majority of patients exhibiting damage to the inferior parietal lobule (Halligan, Fink, Marshall, & Vallar, 2003). Visuospatial neglect describes the condition where one side of the body (typically the left side) exhibits sensory, motor, and attentional deficits, while the unaffected side generally remains unchanged (Halligan et al., 2003). Interestingly, manifestations of left spatial neglect can also appear from lesions in right frontal and right temporal areas (Marshall, Fink, Halligan, & Vallar, 2002). Depending on the location and severity of the lesion, neglect of personal or peripersonal space may be exhibited (Cocchini, Beschin, & Jehkonen, 2001). Symptoms of left personal neglect may include failure to shave the left side of the face, failure to adjust the left side of glasses worn on the face, or proprioceptive deficits in left-sided limbs (Cocchini et al., 2001). Conversely, peripersonal neglect may present without any deficits in personal space; this can be assessed with visual search tasks where targets remain close to the body, within arm’s reach (Cocchini et al., 2001). The differences seen in the manifestations of these conditions suggests that these processes (personal and peripersonal organization) may be represented by distinct neural networks (Halligan et al., 2003).

Fronto-parietal connections are involved in a range of processes, including attention, visuospatial orientation, and spatial cognition (Vallar et al., 1999; Vossel et al., 2014). More specifically, the premotor and posterior parietal cortices have been shown to be active during motor exploration of space (Vallar et al., 1999).

1.5.4. Neural Correlates of Spatial Presence

Spatial navigation tasks and non-interactive VEs have been utilized to identify neural underpinnings of the presence experience (Baumgartner et al., 2008; Baumgartner et al., 2006; Jäncke et al., 2009; Kober et al., 2012; Kober & Neuper, 2011, 2012). Typically, low and high presence conditions are created by altering visual and auditory stimuli, or by changing the properties of the display (i.e. 2D desktop monitor vs. 3D head-mounted display for VR). Changes in subjective presence ratings have been associated with specific activation patterns in prefrontal and parietal areas of the brain (Baumgartner et al., 2008; Baumgartner et al., 2006; Jäncke et al., 2009; Kober et al., 2012; Kroupi et al., 2016). Areas near the posterior parietal cortex are suggested to play an essential role in the organization of the body schema, which incorporates spatial orientation and an egocentric representation of space (Head & Holmes, 1911; Vallar et al., 1999); thus, enhanced neural activity over the parietal region is expected. Baumgartner and colleagues (2008) developed a passive roller coaster simulation for use in functional magnetic resonance imaging (fMRI), and found that prefrontal regions were negatively correlated with presence ratings in adults, though no correlations were found in children. They also discovered that adults who reported lower scores of presence in the more immersive simulation showed increases in blood-oxygenation-level-dependent (BOLD) increments in both the left and right DLPFC (Baumgartner et al., 2008). These findings suggest that lower ratings of presence may be associated with increased activation in frontal brain regions. Baumgartner and colleagues (2008) also suggest the prefrontal cortex may play a modulatory role in the presence experience; increased activity in the frontal region was associated with decreased activity in parietal lobes and a reduced presence rating. Anatomical connections between frontal and parietal areas (Kandel et al., 2013; Vallar et al., 1999) are likely to be associated with the differences found in presence experience, especially since specific frontal regions are not fully matured in children (Baumgartner et al., 2008).

Kober and colleagues (2012) found similar results in an interactive virtual maze, where participants who reported lower presence scores showed increased activity in DLPFC areas. Complementing Baumgartner and colleagues' (2008) work, greater presence scores were associated with increased activity over the parietal lobe (Kober et al., 2012). They also discovered strong connectivity between frontal and parietal regions, which is suggested to play a role in the user's presence experience (Baumgartner et al., 2006; Kober et al., 2012). When examining ERD within the alpha frequency band (8-12 Hz), they found increased desynchronization over parietal areas in the high-presence condition (Kober et al., 2012). Their results also indicated an increase in connectivity between frontal and parietal regions during the less immersive condition. These findings demonstrate the importance of prefrontal and parietal activation in modulating the presence experience during different immersive conditions. It is reasonable to assume that if users are more involved (immersed) in the simulated world, they are more likely to act as if they were situated in the real environment. This idea may help to explain the differences found between low- and high-presence conditions.

Kroupi and colleagues (2016) also identified differences in the high beta frequency (21-29 Hz) during passive observation of 2D and 3D videos, and high- and low-quality videos. They suggest that the high beta band is mainly responsible for distinguishing between videos of high and low reality (Kroupi et al., 2016).

Interactive visuomotor tasks performed in VEs are more relevant to motor learning strategies, compared to the previous studies examining passive spatial presence experience. Lin and colleagues (2012) created a visuomotor tracking task which provided haptic feedback when excessive errors were made. EEG analysis showed alpha band desynchronization near ipsilateral motor regions when participants were provided with haptic feedback (C.-L. Lin et al., 2012). They also found reduced performance errors during haptic feedback trials (C.-L. Lin et al., 2012). This suggests that haptic feedback induces specific patterns of cortical activity, providing task-relevant sensory information resulting in enhanced motor performance.

1.6. SUMMARY

Activities of daily life often require the coordination of both gross and fine motor skills, which are possible through the adaptive nature of our sensorimotor system (Riemann & Lephart, 2002). The sensorimotor system can be described as a complex network involving the stimulation of afferent pathways from external sources, the summation and integration of subsequent action potentials into the CNS, and the excitation of appropriate efferent pathways resulting in the execution of a motor command (Kandel et al., 2013; Riemann & Lephart, 2002). Repetitive practice of movements can enhance spatial and temporal measures of motor performance, which is a fundamental aspect of human behaviour (Willingham, 1998). Neural plasticity associated with training can be adaptive, resulting in enhanced performance, or maladaptive, leading to decreased performance and even pain or overuse injuries.

As technology advances our interactions with interactive multimedia (Frauenberger et al., 2004; Kapralos et al., 2017), it is imperative that we develop an intimate understanding of human-machine interfaces, and how they may influence our cognitive and behavioural processes. Understanding how different sensory modalities influence our perception in VEs is fundamental in expanding our knowledge of motor learning processes, and will provide researchers with crucial information on how to design and implement immersive simulations for education and training. For instance, the addition of footstep sounds allowed slow animations to be perceived as smoother than fast animations, which can be important in the design of immersive simulations without increasing computational requirements of the system (Hulusić et al., 2011). Current literature indicated that multimodal stimuli can effect simple response-time behaviours, without much consideration for more complex tasks requiring greater degrees of attention and coordination. It may be necessary to consider developing occupation-specific training simulations, as there may be certain behavioural and cognitive tasks which are fundamental for some groups of trainees, but irrelevant to others. For instance, practicing tasks which require high levels of spatial awareness and rapid decision making would be extremely beneficial for firefighters navigating a building fire, but perhaps less important for surgical practitioners who rely on haptic cues and fine motor skills to perform optimally.

Non-invasive neurophysiological techniques, such as EEG, have the potential to measure cortical activity patterns at various locations on the scalp, and spectral analysis can identify patterns within certain frequency bands (Klimesch, Schimke, & Pfurtscheller, 1993; Pfurtscheller & Lopes da Silva, 1999; Stancák & Pfurtscheller, 1995). These techniques can examine differences in cortical activation between performing tasks in a VE compared to the same task performed in the real world. The literature suggests that EEG can be used as a marker of the sense of presence in ISEs, but there is minimal work utilizing EEG during haptic feedback and its possible correlation to task performance.

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CHAPTER 2. PROPOSED RESEARCH FRAMEWORK

The proposed research framework will examine sensorimotor integration in healthy adult humans by running two separate but related studies. The first study aims to examine how haptic force-feedback, provided by a consumer device, influences motor performance in a computer-simulated drilling task. Subjective ratings of reality are also examined to identify potential differences in perceived fidelity between haptic and non-haptic trials. The second study, which incorporates the same drilling scenario as the first experiment, uses electroencephalography techniques to investigate patterns of brain activity during both haptic and non-haptic conditions. These studies investigate the possibility of enhancing user experience and motor performance by altering the sensory information available for sensorimotor integration and processing. The proposed research framework incorporates motor behaviour and neurophysiological processes in a simulated motor task, to form a comprehensive study on human behaviour in a simulated drilling task.

CHAPTER 3. MANUSCRIPT 1

Title: Haptic feedback enhances motor performance in a simulated drilling task

Authors: Grant, B. L., Murphy, B. A., Kapralos, B., Uribe-Quevedo, A., Williams-Bell, M., and Yielder, P. C.

3.1. INTRODUCTION

Virtual reality and computer-based simulations, collectively referred to as immersive simulated environments (ISEs), have the unique ability to replicate scenarios in diverse areas, including those pertaining to the acquisition, development, and maintenance of cognitive and psychomotor skills (Siu, Best, Kim, Oleynikov, & Ritter, 2016). ISEs provide a safe, cost-effective alternative to real world environments, which may present challenges that make obtaining adequate practice difficult. Users have the ability to practice rare (and sometimes life-threatening) events in a safe, controlled manner in an ISE, while researchers gather and analyze the user's behaviour and provide feedback, such as accuracy, performance errors, and response time (Coles et al., 2011; Williams-Bell et al., 2015). Users can perform multiple iterations of a task with relevant feedback to develop proficiency before taking their skills to the real world, where cognitive and psychomotor errors can result in serious consequences. Practicing new motor skills is essential to optimize performance (Maxwell, Masters, Kerr, & Weedon, 2001), however, it is not clear how various sensory percepts experienced during training impact skill acquisition and learning.

As interactive multimedia technology advances and virtual worlds become more real, we have an increasing need to expand our understanding on how ISEs impact human brain function and task performance. ISEs can be incredibly useful for rehabilitation and training purposes, especially within high-stress occupations, such as medical professionals, firefighters, and military personnel (Coles et al., 2011; Cox et al., 2010; Williams-Bell et al., 2015). When individuals with these occupations make performance errors, it is likely at the expense of individual or public safety. It is essential that we understand how to reduce the risk of these errors, and it is possible that repeated exposure to real world scenarios can enhance the user's cognitive and psychomotor behaviour while performing tasks. Computer graphics technology has greatly enhanced visual immersion by providing realistic rendering of computer-generated worlds, while other sensory feedback, such as auditory and touch, have seen growing research with recent advances in consumer-level technologies (Flavián et al., 2019). In a real environment, our senses are constantly stimulated by external percepts, providing crucial information to be organized and integrated through the act of multisensory integration (Seitz et al., 2007). Our senses also interact with one another, influencing this integration process as well as our own perception of the world around us. The way we perceive our environment, and how we can act within it, is determined by the way our senses interact (Kapralos et al., 2017). Little research has been done to consider how haptic sensation may alter the other senses, despite the importance of touch in our daily lives. Haptic perception refers to sensation through touch and manipulation, which includes both tactile and kinesthetic stimuli (Culbertson et al., 2018; Srinivasan, 2016). Without haptic perception, we would have great difficulty discriminating textures between multiple surfaces, and we would struggle to grasp and manipulate objects. The field of haptics largely consists of information acquisition by machines, humans, or a combination of the two – these interactions can take place in a real or simulated environment (Melaisi et al., 2018; Srinivasan, 2016). The sense of touch is incredibly important for discovering information about objects near us – simulating this sense can be difficult, as it requires realistic sensation of pressure, texture, movement, and vibrations, which are limited by inherent limitations of diverse actuators (Culbertson et al., 2018; Melaisi et al., 2018).

Low-end haptic devices are available to consumers and are relatively inexpensive, however, they may not replicate real-world operations as closely as their high-end counterparts in terms of force feedback, resolution, and refresh rate (Melaisi et al., 2018). Low-fidelity haptics provide simple vibration stimuli from different motors, and are found in devices such as video-game controllers, portable gaming consoles, haptic gloves, and in mobile devices (Melaisi et al., 2018). Other low-end haptic devices employ serial, parallel, and other mechanisms to provide force and tactile feedback (Melaisi et al., 2018). In order to accurately replicate real-world tasks, these devices often need higher levels of fidelity and range of motion (degrees-of-freedom), which low-end haptics fail to provide (Coles et al., 2009). Devices with high levels of haptic fidelity can be costly and are often utilized in tasks requiring precision, such as in teleoperations – in delicate surgical procedures using robotics, and when astronauts operate robots for external repairs on the International Space Station (Culbertson et al., 2018). Research has shown the importance of high-end haptics in the medical field: advanced computer simulations allow student practitioners to train on virtual patients while receiving feedback on their performance, and often haptics in the form of force-feedback is used to replicate the mechanical properties of individual organs, tissues, or entire cadavers (Basdogan et al., 2004; Coles et al., 2011). High-end haptic devices can certainly provide more tactile information regarding surface properties, however, access may be limited due to the costs associated to maintenance, infrastructure, and acquisition for large groups of trainees. It is still uncertain whether the increased haptic fidelity in high-end devices are beneficial in regards to enhanced motor performance and learning (Melaisi et al., 2018). If low-fidelity haptic devices utilized in an ISE can achieve high levels of performance and retention, and enhance the user's simulation experience, then they may be useful devices for training-based simulations.

Research suggests that simultaneous exposure to multiple sensory modalities can influence a user's perception, and interactions between congruent stimuli can be beneficial for performance, in terms of reaction time and reduced errors (McCracken et al., 2019; Melaisi et al., 2018). Perception of our own body in space is a fundamental coordination of proprioceptive and kinesthetic information, which is required by interactions with the world around us (Maravita et al., 2003; Roll, Roll, & Velay, 1991). Awareness of joint position allows us to sustain posture and execute movements efficiently (Roll et al., 1991). This awareness of our body's posture and limb coordination is classically known as 'body schema' (Gallagher, 1986). Body schema has been studied extensively in the psychology domain, but still requires attention from the neuroscience field. Research suggests that the primate brain constructs internal body-centered representations that can be modified following a period of tool-use, which extends the reachable space near the user (peripersonal space) (Iriki et al., 1996; Maravita et al., 2002). With prolonged use, a tool can become an extension of the hand, in regards to our internal body representation (Maravita et al., 2003). In theory, this should also apply to objects or machinery that a user regularly interacts with. The plasticity of our body schema is fundamental for the ability to manipulate objects and gather information from our environment.

Force and tactile stimuli are both important in our haptic perception: force and torque feedback resists a user's respective motion and rotation, whereas tactile feedback detects surface textures and is responsible for two-point discrimination (Culbertson et al., 2018; Gregory, 1967). Force/torque stimuli from an object effectively provide us with kinesthetic information from muscle spindles and Golgi tendon bodies (Coles et al., 2011; Culbertson et al., 2018). Tactile stimuli, such as vibrations, can stimulate a variety of specialized cells highly populated in the finger tips and the palm of the hand: mechanoreceptors such as Meissner's corpuscles and Merkel cells are sensitive to light touch and vibrations, while lamellar corpuscles can also detect pressure (Coles et al., 2011; Culbertson et al., 2018). Both force and tactile sensations provide information for optimal haptic perception, and should be considered when a user's presence is imperative to a simulated task.

While most sensorimotor research focuses on simple, static stimuli, a recent emergence of dynamic, multimodal research (multiple percepts appearing concurrently) may be more applicable to real-world scenarios (Melaisi, Nguyen, Uribe, & Kapralos, 2017; Parsons, 2015). We are constantly engaging with various stimuli, and when two or more sensory inputs are congruent and presented simultaneously, we are able to process and respond to our environment more quickly than if the stimuli were presented separately (Laurienti, Kraft, Maldjian, Burdette, & Wallace, 2004; McCracken et al., 2019). Visual and auditory interactions are among the most studied, however, there is an increase in research investigating haptic interactions and human behaviour (Coles et al., 2011; Culbertson et al., 2018; Melaisi et al., 2018). Manipulating auditory stimuli in video games can influence a user's play experience, which ultimately affects their feelings of presence (Lipscomb & Zehnder, 2004; Melaisi et al., 2018). Sound can even impact our physiology, as discussed in a recent study that found an increase in cortisol levels during video game play with music, as compared to the same game without music (Hébert, Béland, Dionne-Fournelle, Crête, & Lupien, 2005).

Some research suggests that the sense of touch gives us direct features from our environment, while visual stimuli provides us with ambiguous sensory information (therefore requiring further processing in the brain) (Gregory, 1967). Visual dominance, however, is a well-known phenomenon in the psychophysiological domain that explains how visual stimuli typically dominate other percepts (i.e., audition, proprioception, etc.) and drives the multimodal interaction (Hecht & Reiner, 2009; Posner, Nissen, & Klein, 1976). Hartcher-O'Brien and colleagues (2008) conducted a series of studies to observe if vision also dominates the sense of touch. They found that during a speeded discrimination task, participants made more visual-only responses than tactile-only responses in bimodal trials (Hartcher-O'Brien et al., 2008). It is clear that vision plays a critical role in responses that require speed, however, most of these studies use simple response paradigms, where the haptic information provided is not task-relevant. Lin and colleagues (2012) found that participants made less errors and adjustments when receiving haptic feedback in a visuomotor tracking task, as compared to not receiving haptic feedback. However, their study included a haptic joystick as the haptic interface, which may not be relevant to tasks performed in the real world. These results indicate that greater research is required to explore how task-relevant haptic feedback can influence motor learning adaptations and performance in simulations and VEs.

The current study uses task-relevant haptic feedback (via a drilling simulation) to explore the role of low-fidelity haptic sensation in combination with auditory stimuli on motor performance and subjective ratings of reality. Our hypothesis being that haptics in the form of force-feedback will enhance a user's performance in the form of reduced errors, and increase ratings of perceived realness in a drilling simulation.

3.2. EXPERIMENTAL PROTOCOL

A drilling simulation was used for this experiment, in order to examine effects of task-relevant haptic feedback on motor performance. The task was to drill 2 cm into a block of wood, displayed on a computer monitor. This study included a familiarization phase and an experimental phase to ensure participants understood the task. The familiarization phase included an average of 8-10 trials for each condition (approximately 16-20 trials in total), or until the participant felt comfortable with both haptic and non-haptic conditions. All participants completed no more than 20 trials during the familiarization phase. Experimental trials were randomized so participants could not predict the order of trials. After each trial was completed, a subjective presence scale was presented as a continuous linear visual analogue scale. This type of rating scale was used to deter participants from remembering previous ratings. Figure 1 demonstrates an overview of the trials presented in the experimental protocol.

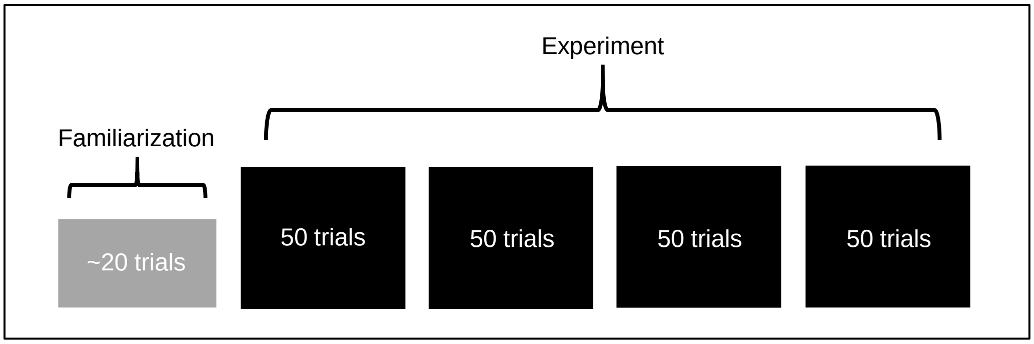

Figure 1. Experimental protocol. Grey block represents familiarization trials; black blocks represent experimental trials. Spaces in between the experimental blocks indicate the allotted five-minute breaks.

3.3. METHODS AND MATERIALS

3.3.1. Participants

Participants were volunteers recruited from the student population of Ontario Tech University, in Oshawa, Canada. Ten males and eight females participated in the study for a total of 18 participants. Inclusion criteria required right-handedness and prior experience using a drill – four participants indicated that they had never used a drill before, so they were excluded from performance and subjective rating data analysis. Participants recruited were apparently healthy young adults, aged 22.9 (± 1.4) years old, and self-reported normal hearing, and normal or corrected-to-normal vision (n = 14).

Before the experiment began, all participants completed the Edinburgh Handedness Questionnaire, which assessed which hand was most dominant (right, left, or ambidextrous). Thirteen participants reported right-handedness, while one participant was ambidextrous. All participants were required to operate the drill with their dominant (right) hand.

3.3.2. Procedure

All experiments took place within the Human Neurophysiology and Rehabilitation Lab at Ontario Tech University in Oshawa, Canada. Only the participant, the student research lead, and one research assistant was present at the time of all experiments.

Participants were seated on a chair in front of a desk, facing a 23-inch display monitor (LG, Soeul, South Korea) and the Novint Falcon haptic device. Seat arrangement was adjusted by asking participants to find a comfortable position (facing monitor, feet planted on ground) while grasping the Falcon and moving the device through its range of motion. Distance was measured from the participants' eyes to the desktop monitor; on average, participants were seated 71.9 cm (± 4.8 cm) away from the display. Speakers were set up directly below the display, to ensure visual and auditory stimuli were spatially congruent. Prior to the start of the experiment, participants completed a familiarization phase, performing multiple trials of both haptic and non-haptic conditions.

During the familiarization phase, participants were instructed to complete as many trials as needed until they felt confident in their ability to perform the task, which ultimately required no more than 16-20 total trials. They were informed that their drill depth target was two centimeters (2 cm), while they had the ability to see a side-view of the simulation, showing how far the drill bit drilled into the wood (Figure 2A). This immediate visual feedback allowed participants to see exactly how far the drill bit moved into the wood.

After completing the familiarization phase, each participant completed a total of 200 pseudo-randomized trials: 100 haptic and 100 non-haptic. The first block of 100 trials were randomized – after completion, this same block of trials was repeated. Three- to five-minute breaks were allotted every 50 trials, or upon the participants request. In both conditions, auditory stimuli were consistent, while force-feedback was only provided during the haptic condition. Only the front-view of the simulation was visible to participants during the experimental phase (Figure 2B): this lack of adequate visual information attempts to isolate the effects of haptic sensation (Melaisi et al., 2018). After each trial, participants were asked to rate how real the trial felt, which was prompted by the following text: “Please rate how real your drilling experience was for this trial”. These scores were interpreted as the participants’ experience of reality. The rating scale was a modified continuous linear visual analogue scale (Figure 2C). For each trial, drilled depth and subjective rating were recorded.

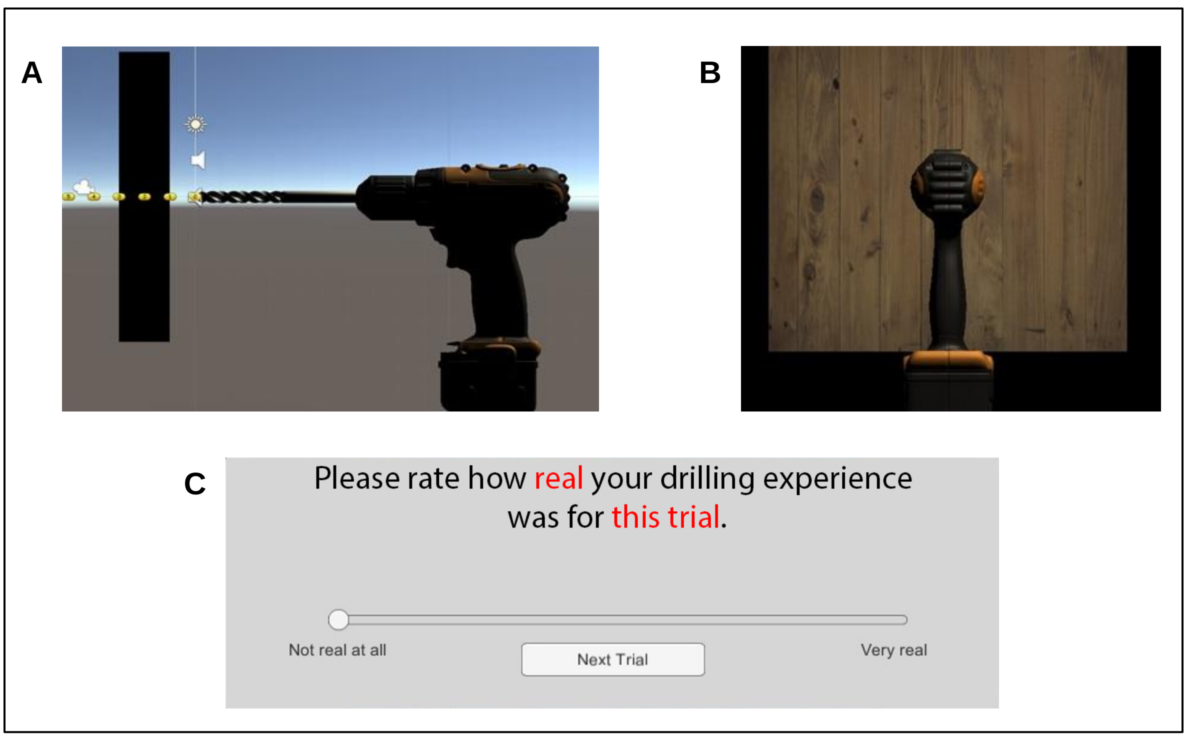

Figure 2. Simulation scenes. (**A**) Side view visible only during familiarization trials. (**B**) Front view shown throughout experimental trials. (**C**) Subjective rating scale presented after each trial.

3.3.3. Experimental Sequence

1. Drilling Simulation

A drilling scenario was selected for this study because haptic feedback plays an important role in operating a drill, as it provides the user with important sensory information regarding the task. The drilling simulation was created using Unity game engine, developed by Unity Technologies (San Francisco, California, USA), and was utilized in previous simulation research by Melaisi and colleagues (2018) at Ontario Tech University.

The Novint Falcon, a low-fidelity haptic device by Novint Technologies (Albuquerque, New Mexico, USA), was used as a haptic controller and provided force-feedback in the haptic trials (Figure 3). The Falcon has three-degrees-of-freedom, and provides up to 9.0 N of force-feedback, with a resolution of 400 dpi (dots-per-inch). A light-weight mock-drill attachment was 3D-printed and acted as the haptic interface – the use of a realistic device may be more relevant when attempting to simulate specific tasks. The drill attachment was light-weight, more similar in mass to a surgical drill, which was chosen to reduce the impact of strength differences between participants.

The task was to drill 2 cm into a block of wood. While the drilling environment and the block of wood itself were computer simulated, users were able to operate the Falcon device in place of a real drill. Participants were able to grasp and push the Falcon, which would move the virtual drill closer to the block of wood. Audio recordings were played throughout the simulation, and indicated when the drill initially contacted the wood. When participants considered they had drilled 2 cm, they pulled their arm back to the starting positon.

Figure 3. Novint Falcon. Haptic device with mock drill attachment.

2. Auditory Stimuli

Simulating the sense of hearing, or audition, is becoming more prevalent in immersive multimedia, likely due to an increase in human-machine interfaces (Frauenberger et al., 2004). Different types of music have even been shown to alter cortisol levels during video game play (Hébert et al., 2005), suggesting that sound plays a crucial physiological role during the performance of tasks.

The drilling sounds used in this simulation were actual recordings from a Stanley Black and Decker (Connecticut, USA) consumer drill, drilling in open air and through wood. The recordings were made in an audiometric room to limit external noise and reverberation of sounds within the environment (Melaisi et al., 2018). The “air” drill recording started with the start of the simulation and stopped once the drill bit made contact with the virtual block of wood. The “wood” drill recording started when the drill bit made initial contact with the wood, and was looped to play throughout the drilling movement. These recordings allowed the auditory stimuli to be synchronized with the movements of the user – however, the recording sound did not change with the depth of the material, nor with pressure changes from the user. This type of sound effect is commonly used in simulations of this nature (Melaisi et al., 2018). Frequency changes in response to altered pressure and sound effects from material depth would be incredibly time-consuming, and are unlikely to be used in basic simulations such as the one presented in this study. All auditory stimuli were presented via external Sony (Tokyo, Japan) speakers, and were presented at the same volume for all participants.

3. Haptic Stimuli

Once a user pushed the drill to contact the block of wood during a haptic trial, the Falcon provided force-feedback (the feedback occurred upon contact of the head of the drill bit with the block of wood). Both auditory and haptic stimuli were presented to the user at the same time (the ‘wood’ audio recording and haptic force-feedback). Participants drilled to the target and returned the Falcon to the starting position. This haptic stimuli was only presented during the haptic condition trials.

3.4. DATA ANALYSIS

Performance data and subjective rating data were analyzed for each participant, in both haptic and non-haptic conditions. Drilled depth errors and average ratings of reality were calculated for every participant in both conditions. Statistical analyses were performed in a repeated measures-design, to examine any differences between haptic and non-haptic conditions.

3.4.1. Analysis of Performance Data

Performance error is commonly measured during movement tasks, and is typically measured by obtaining an average amount of errors over a number of trials (Burkitt, Staite, Yeung, Elliott, & Lyons, 2015; Elliott, Hansen, Mendoza, & Tremblay, 2004; C.-L. Lin et al., 2012) Performance data was obtained from all participants by measuring drilled depth and calculating absolute error, constant error, and variable error. Absolute error was calculated by taking the absolute value of subtracting the target depth from the actual drilled depth, while constant error was calculated by subtracting the target depth from the actual drilled depth. Standard deviations were used as variable error in each condition.

$$\text{Absolute Error} = |\text{average drilled depth} - \text{target depth}|$$

$$\text{Constant Error} = \text{average drilled depth} - \text{target depth}$$

$$\text{Variable Error} = \sqrt{\frac{\Sigma\,(x - \bar{x})^2}{n}} \text{ or standard deviation}$$

3.4.2. Analysis of Subjective Reality Data

Subjective user experience ratings are commonly used in VEs in order to gain insight in simulation design, and to further enhance our understanding of how different immersive scenarios can alter brain activity (Baumgartner et al., 2008; Baumgartner et al., 2006; Kober et al., 2012). In this study, subjective ratings of reality were obtained from all participants on a trial-by-trial basis. A continuous linear visual analogue scale was used to measure subjective reality, with participants clicking and dragging a computer mouse to a desired position along the scale to select their rating. The rating scale ranged from “not real at all” (0), to “very real” (10). Each score was recorded by Unity and output to a CSV file.

3.4.3. Statistical Analysis

Mean drilled depth, absolute error, constant error, and variable error were calculated per participant in response to each condition (haptic and non-haptic). Mean presence score was also calculated for both haptic and non-haptic conditions per participant. Outliers outside ± 2 standard deviations were removed prior to statistical testing. A 4 performance measure (drilled depth, absolute error, constant error, and variable error) by 2 condition (haptic and non-haptic) multivariate analysis of variance (MANOVA), with repeated measures on the last factor, was conducted to determine significant differences in performance accuracy. Subjective ratings were assessed for both haptic and non-haptic trials, using a paired samples *t*-test to compare differences between the two conditions. Alpha was set at $p = 0.05$, and partial eta squared (η_p^2) values were reported for effect size, where 0.01 indicated a small effect, 0.06 as medium, and 0.14 as a large effect size (Richardson, 2011). All statistical tests were run using SPSS version 24 (Armonk, New York, USA). All data was checked for normality using Shapiro-Wilk's test.

3.5. RESULTS

3.5.1. Performance Data

MANOVA results revealed a statistically significant main effect of Condition ($F_{(3,11)} = 63.684$, $p < 0.0001$, $\eta_p^2 = 0.946$).

Drilled Depth Results

Figure 4 shows the drilled depth mean and standard error of the mean (SE) in both haptic and non-haptic conditions. Univariate testing within the MANOVA indicated significance in the Condition by Drilled Depth interaction ($F_{(1,13)} = 92.044$, $p < 0.0001$, $\eta_p^2 = 0.876$). These results show that users drilled significantly further into the wood during the non-haptic condition (5.5 cm ± 0.52 cm), as compared to the haptic condition (0.9 cm ± 0.14 cm).

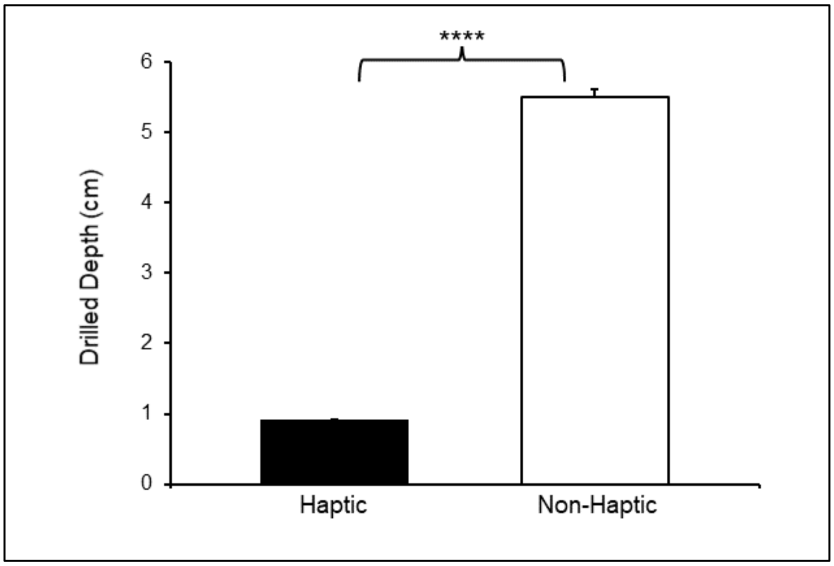

Figure 4. Drilled depth results. Mean and SE of drilled depth in centimeters with and without haptic feedback. Statistical results are noted as *p<0.05, **p<0.01, ***p<0.001, and ****p<0.0001.

Accuracy Results

Figure 5 shows the mean and SE of performance errors in haptic and non-haptic conditions. Univariate testing within the MANOVA indicated a significant Condition by Absolute Error interaction ($F_{(1,13)} = 17.587$, $p = 0.001$, $\eta_p^2 = 0.58$), implying that participants made more errors in the non-haptic condition (3.5 cm ± 0.52 cm), as compared to the haptic condition (1.1 cm ± 0.14 cm). Significant differences were also found in the Condition by Constant Error interaction ($F_{(1,13)} = 21.196$, $p < 0.0001$, $\eta_p^2 = 0.88$), demonstrating negative errors in the haptic condition (-1.1 cm ± 0.14 cm), as compared to the non-haptic condition (3.5 cm ± 0.52 cm). Significance was also found in the Condition by Variable Error interaction ($F_{(1,13)} = 0.841$, $p < 0.0001$, $\eta_p^2 = 0.74$), revealing greater variability in the non-haptic trials (0.96 cm ± 0.09 cm), as compared to the haptic trials (0.37

cm ± 0.06 cm). These results indicate that participants made less errors with haptic feedback.

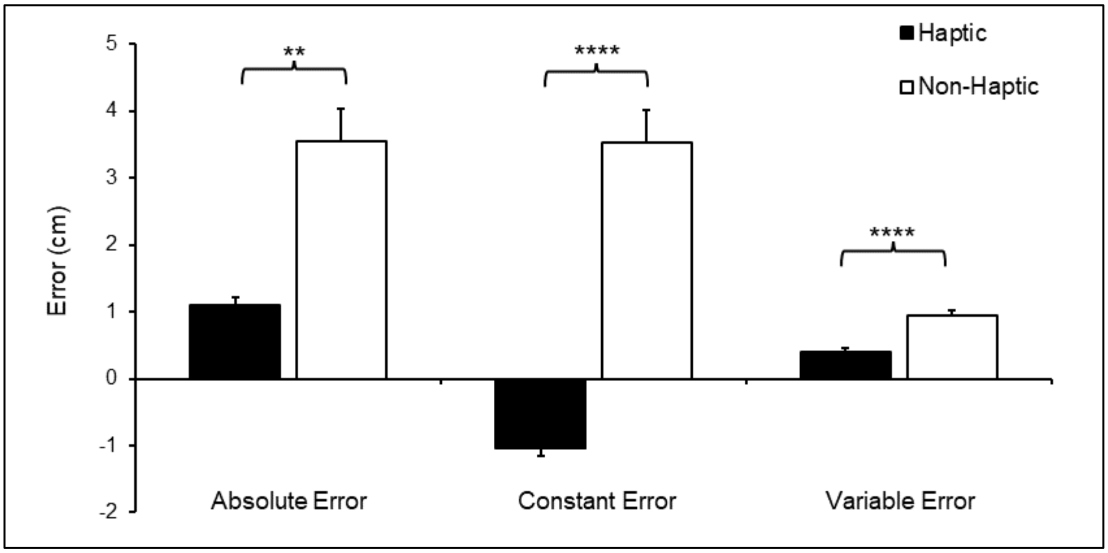

Figure 5. Performance results. Mean and SE of performance error in centimeters of all participants. Statistical results are noted as *p<0.05, **p<0.01, ***p<0.001, and ****p<0.0001.

Subjective Reality Results

Figure 6 shows the mean and SE of subjective reality scores on a scale of 0 (not real at all) to 10 (very real). A paired samples *t*-test revealed a significant difference between the haptic and non-haptic conditions, $t_{(12)} = 25.745$, $p < 0.0001$. These results indicate that the haptic condition (8.1 ± 0.9) provided significantly higher levels of reality compared to the non-haptic condition (0.9 ± 0.8).

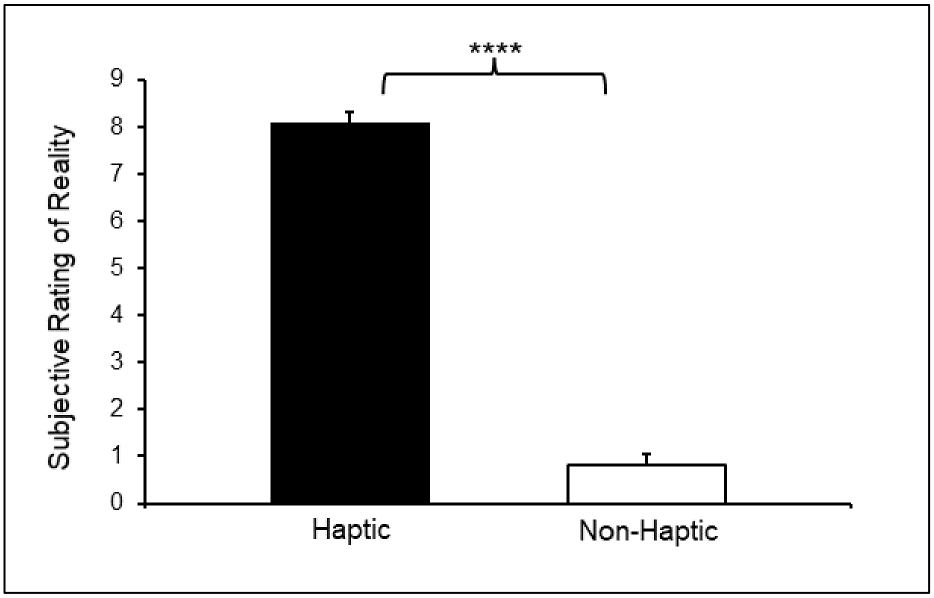

Figure 6. Subjective reality rating results. Mean and SE of subjective rating in haptic and non-haptic conditions. Statistical results are noted as *p<0.05, **p<0.01, ***p<0.001, and ****p<0.0001

3.6. DISCUSSION

This study explored how haptic force-feedback can impact a task where tactile and kinesthetic sensations are critical for performance in the real world (ie. drilling into a piece of wood). Absolute, constant, and variable errors of drilled depth were significantly reduced during haptic feedback trials, supporting our hypothesis.

An external stimulus associated with a motor command can be useful for motor learning, and when practicing optimal behavior with these stimuli (visual, auditory, and tactile), motor skill performance can improve (C.-L. Lin et al., 2012; Maxwell et al., 2001). Absolute error results suggest that haptic feedback increased performance accuracy in a simulated drilling task. This shows the importance that haptic feedback has on the execution of accurate movements, which is supported by previous research (Coles et al., 2011; C.-L. Lin et al., 2012; C.-T. Lin, Lin, Huang, Chen, & Tung, 2010). Lin and colleagues (2012) concluded that haptic feedback enhanced motor learning in a tracking task, and these results were accompanied by differences in brain activity between haptic and non-haptic performances. These findings demonstrate the importance of using task-relevant haptic feedback during motor skill acquisition.

Constant and variable errors reveal that users consistently under-drilled during haptic trials – similar to the behavior of undershooting targets in reaching and aiming studies (Engelbrecht, Berthier, & O'Sullivan, 2003; Roberts, Burkitt, Elliott, & Lyons, 2016). Research suggests that an initial undershoot towards a target requires less time and energy to correct when compared to overshooting (Elliott et al., 2004; Lyons, Hansen, Hurding, & Elliott, 2006). Overshooting requires the limb to travel further and decelerate in order to return to the target, thus firing alternate muscle groups and slowing down the performance of the task (Elliott et al., 2004; Engelbrecht et al., 2003). Undershooting a target is optimal behavior in reaching and aiming tasks (Engelbrecht et al., 2003) and even persists with movements involving mass (Burkitt et al., 2015). These findings have real world implications, as in most drilling tasks it is critical not to overshoot. The fact that participants were more accurate, undershooting by an average of one centimeter, as compared to dramatically overshooting in the absence of haptic feedback, indicates how critical haptic sensation is to accurate motor performance.

Although the findings of this study suggest that haptic feedback enhances performance, Melaisi and colleagues (2018) previously found that participants were more accurate when drilling to a depth of 5 cm as opposed to 2 cm. When exposed to haptic feedback during a drilling simulation, they found that participants drilled for the same amount of time, regardless of the target depth (either 2 cm or 5 cm) (Melaisi et al., 2018). Since the current study did not have a haptic only condition (i.e. no auditory feedback condition) and only tested the 2 cm depth, we cannot directly compare our findings to theirs.

Despite being a low-end device, the Falcon provided haptic information that allowed user's to experience a realistic drilling process. User experience is a fundamental aspect of simulations, whether they are used for entertainment, education, or training. This study found that participants rated the haptic trials significantly higher in terms of realness when compared to the non-haptic trials, which supports our hypothesis. These results demonstrate that low-end haptics, when used in a relevant context, can provide enough haptic sensation to enhance ratings of reality, when compared to trials without haptic feedback. It is likely that audiohaptic interactions were able to influence a user's experience, leading to a more realistic perception of the simulated environment. These results verify prior findings from Melaisi and colleagues (2017), who found that users perceived the highest level of haptic fidelity in a drilling task when presented with a drill audio recording, compared to listening to classical music, heavy metal, white noise, or no sound at all. The same participants also felt that sound was an important aspect on their haptic experience, which highlights the importance of contextual stimuli (Melaisi et al., 2017). The current study builds on this research and indicates that even low-fidelity haptic stimuli can enhance a user's experience when combined with congruent audio stimuli.

This study had participants seated in front of a computer simulation, which may not represent most drilling scenarios. Although seated positions are common in these types of simulations, it is possible that this protocol could have affected participants' perception of the task. However, our results indicate large effect sizes for all statistically significant findings, so postural positioning is unlikely to have drastically influenced our results. For future simulation studies, it is recommended to examine the effects of body position on task performance and perception of haptic fidelity.

To support the findings of this study, future studies should compare the results of the simulation to those with a higher-end device or a real drill. This would provide us with more information regarding haptic fidelity and the overall perception of the simulation experience. Motor learning also involves skill retention, which we did not test for in this study. Manipulating the experiment to create a more difficult task, and adding a second session the following day to assess skill retention could provide us with critical information on the motor learning process. It is also possible that drilling to shallow depths provides more difficulty for participants, in which case future studies could explore the effects of altering the target depth.

3.7. CONCLUSIONS

The present study found that task-relevant audiohaptic stimuli improved performance accuracy and subjective ratings of reality during a simple drilling task, as compared to audio alone. As technology advances, the importance of multisensory interactions within multimedia only grows. While much of this research involves entertainment-based simulations, such as video-games, there is an increasing need to evaluate the use of multimodal stimuli in training-based simulations. It is critical to understand the contribution of different types of sensory feedback and their influence on task performance and perception in ISEs. This understanding is fundamental for informing the development and design process of future training-based simulations.

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CHAPTER 4. MANUSCRIPT 2

Title: Event-related desynchronization in an interactive drilling simulation with and without haptic feedback

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4.1. INTRODUCTION

Immersive simulation environments (ISEs), which include virtual reality and computer-based simulations, attempt to create a realistic setting which immerses the user into believing they are in the real world. Our perception of the environment is possible through the integration and interpretation of various percepts, which constantly bombard our senses with ambiguous information. Different sensory stimuli can alter our ability to process multiple percepts, influencing our perception of our surroundings. Our brain's ability to organize and interpret this information is crucial for interacting with our environment and coordinating efficient movements (Seitz et al., 2007). By manipulating external stimuli within an ISE, we can influence a user's perception of the environment, thus altering their presence experience. Presence is the term used to describe the sense of "being there" in a virtual environment, when a user is transiently unaware of their physical location, while perceiving oneself to be situated within the VE (Baumgartner et al., 2008; Wirth et al., 2007). An important quality of these simulations is an egocentric viewpoint, which greatly enhances presence and the subsequent user experience (Baumgartner et al., 2008).

Incorporating the touch sensation into VEs has increased over the past two decades, as haptic rendering in simulations has grown from simple vibrations to graspable devices providing force-feedback, and wearable devices such as haptic vests and gloves (Culbertson et al., 2018). In Manuscript 1, we examined motor performance of a simulated drilling task using a low-fidelity haptic device, which provided the user with haptic force-feedback. Study 1 findings indicated greater performance accuracy during trials with haptic feedback as compared to trials without feedback. Motor skill acquisition and learning has been associated with plastic changes at sensory and motor areas of the cerebral cortex (Boudreau, Farina, Oppenhagen, et al., 2010; Classen et al., 1998; Kleim et al., 2002), however, work is still needed to examine the transferability of learning in a

VE compared to a real environment, and its impact on the neuroplastic changes associated with motor learning.

Prior motor learning research has explored both intrinsic and extrinsic factors leading to enhanced motor performance. Intrinsic factors may include behavioural and physiological aspects of the individual, while extrinsic factors include trainer instructions and feedback (Sigrist, Rauter, Riener, & Wolf, 2013). Augmented feedback describes the knowledge-of-performance or knowledge-of-results information given to an individual with respect to a performed motor skill (Magill, 1994). This feedback can be visually displayed on a monitor, presented as an auditory cue, delivered by a haptic stimulus, or some combination of stimuli (Sigrist et al., 2013). Multimodal interactions, or the amalgamation of multiple senses, can induce specific cortical changes at areas involved in multisensory and sensorimotor processing (Kober & Neuper, 2012; C.-L. Lin et al., 2012; McCracken et al., 2019). These cortical changes coincide with adaptive behaviours, such as enhanced performance, reduced errors, and diminished reaction times (C.-L. Lin et al., 2012; McCracken et al., 2019). Acquisition and learning of complex motor skills seems to benefit from concurrent (real-time) visual feedback (Sigrist et al., 2013). In early learning stages, concurrent feedback may provide a form of guidance, making complex tasks seem easier and preventing cognitive overload (Sigrist et al., 2013; Wulf & Shea, 2002). In contrast to concurrent feedback, terminal feedback is provided after skill performance, and can facilitate motor learning by inducing self-estimations of movement errors (Van Vliet & Wulf, 2006). Human-machine haptic interactions can provide tactile and kinesthetic feedback, which can enhance motor performance during a visuomotor tracking task (C.-L. Lin et al., 2012). Haptic guidance mechanisms have been suggested to influence sensorimotor plasticity, reinforce movement patterns with repetitions, and increase user motivation (Marchal-Crespo & Reinkensmeyer, 2009; Sigrist et al., 2013). Many training and educational applications require precise motor control, giving rise to the integration of haptic devices in immersive environments. High quality haptic devices, providing higher levels of fidelity, are incredibly cost prohibitive, and largely inaccessible to the consumer (Coles et al., 2011; Culbertson et al., 2018). Lower quality devices are most cost effective, however, there is still work to be done to determine if low-fidelity devices can provide adequate haptic feedback for enhanced performance to replace high-fidelity devices.

Two major brain regions are suspected to be highly involved in the user's experience of presence: the prefrontal cortex (PFC) and the parietal lobe (Baumgartner et al., 2008; Baumgartner et al., 2006; Jäncke et al., 2009; Kober et al., 2012). Baumgartner and colleagues (2008) developed a non-interactive roller coaster simulation for use in functional magnetic resonance imaging (fMRI), and found that activity in prefrontal regions were negatively correlated with presence ratings in adults, where increased frontal activity was associated with lower ratings of spatial presence. No such correlation was found in children participants (Baumgartner et al., 2008). They also discovered that a more immersive simulation induced an increase in blood-oxygenation-level-dependent (BOLD) increments in the bilateral dorsolateral prefrontal cortex (DLPFC) of adults who reported lower presence scores (Baumgartner et al., 2008). These findings suggest that lower ratings of presence may be associated with more activation in frontal brain regions, more specifically the DLPFC. They also suggest that the PFC may play a modulatory role in the presence experience, as their findings suggest that increased PFC activity may be associated with decreased activity in parietal lobes, and a reduced rating of presence (Baumgartner et al., 2008). Anatomical connections between frontal and parietal areas (Jäncke et al., 2009; Vallar et al., 1999) may be associated with the differences found in presence experience, especially since some frontal regions are not fully matured in young children (Baumgartner et al., 2008).

Kober and colleagues (2012) found similar results in an interactive maze VE, where participants who reported lower presence scores showed an increase in activity within DLPFC areas. In contrast, increased parietal activation was associated with increases in presence scores (Kober et al., 2012). They also discovered strong connectivity between frontal and parietal regions, which may be able to influence the user's presence experience (Baumgartner et al., 2006; Kober et al., 2012). When examining event-related desynchronization (ERD) within the alpha frequency band (8-12 Hz), they found increased ERD over parietal areas in a highly immersive simulation, compared to a lower-quality simulation (Kober et al., 2012). Alpha band ERD can be interpreted as a correlate of activated cortical areas (Pfurtscheller, Stancak Jr, & Neuper, 1996). Findings also indicated an increase in connectivity between frontal and parietal regions during the less immersive condition. These findings demonstrate the importance of prefrontal and parietal activation in modulating the presence experience during different immersive conditions. Kroupi and colleagues (2016) also identified differences in the high beta frequency (21-29 Hz) during passive observation of 2D and 3D videos, and high- and low-quality videos. Based on their findings, they suggest that the high beta band is highly involved in distinguishing between videos of high and low reality (Kroupi et al., 2016).

Interactive visuomotor tasks performed in VEs are more relevant to motor learning strategies, compared to the previous non-interactive studies examining spatial presence experience. Lin and colleagues (2012) created a visuomotor tracking task which provided haptic feedback when excessive errors (≥ 3 pixels) were made. ERD analysis showed alpha band suppression near ipsilateral motor regions when participants were provided with haptic feedback (C.-L. Lin et al., 2012). They also found reduced performance errors during haptic feedback trials (C.-L. Lin et al., 2012). This suggests that haptic feedback induces specific patterns of cortical activity, providing task-relevant sensory information which results in enhanced motor performance.

These studies suggest a possible similarity in the neural patterns induced by both interactive and non-interactive simulations, across different types of spatial tasks. Supported by prior research, Manuscript 1 found that synchronous haptic feedback along with contextual auditory stimuli can increase the subjective experience of reality in a low-fidelity drilling simulation, as well as enhance motor performance by reducing accuracy errors. Behavioural changes in response to practicing a motor skill can be indicative of motor cortex plasticity - therefore it is of interest to determine whether altered patterns of neural activity exist alongside the observed changes in performance.

The alpha frequency band (7-13 Hz) is often studied when assessing neural responses to motor skill acquisition, as the 10 Hz oscillations are thought to reflect somatosensory function (Hari & Salmelin, 1997). Low alpha ERD (7-10 Hz) can be observed over widespread areas of the cortex in response to a variety of tasks, and likely signifies attention processes and general task demands (Pfurtscheller & Lopes da Silva, 1999). Upper alpha desynchronization (10-12 Hz) has been observed in more restricted cortical areas, localized to parieto-occipital regions (Klimesch et al., 1993). It has been suggested that this desynchronization is associated with sensory-semantic processing, where higher levels of attention are required to encode information (Klimesch et al., 1996; Pfurtscheller & Lopes da Silva, 1999). ERD can be also be observed in upper alpha and lower beta (13-21 Hz) frequency bands during voluntary movements, appearing near cortical sensorimotor areas (Alegre et al., 2002; Pfurtscheller & Aranibar, 1979). Beta ERD typically begins 1.5 seconds before movement-onset, suggesting a relation to movement preparation (Alegre et al., 2002). The 20 Hz cortical frequency within beta bands has been observed over motor regions, reflecting an association with motor function (Hari & Salmelin, 1997).

Alpha and beta bands are generally divided into low and high frequencies to determine any variations within the bands. The low alpha band signifies frequencies from 8-9.5 Hz, while upper alpha denotes 10-13 Hz (Pfurtscheller & Aranibar, 1979; Pfurtscheller & Lopes da Silva, 1999). Low beta represents 13-21 Hz oscillations, while the high beta band signifies 21-30 Hz frequencies (Alegre et al., 2002; Kroupi et al., 2016; Pfurtscheller & Aranibar, 1979).

The current preliminary study aims to explore if there are any underlying neural markers, or specific brain activation patterns, to distinguish between trials with and without haptic feedback. A secondary objective was to calculate effect sizes and observed power to allow sample size calculations for future studies exploring the neurophysiological effects of performing multimodal tasks in ISEs.

Our hypothesis for the current study is that haptic feedback in a drilling simulation will lead to enhanced alpha ERD over cortical areas thought to be responsible for sensorimotor integration (frontal and central regions). We also believe that greater ERD will be found in the parietal region during the haptic trials, as a result of the increased sensory information provided by the haptic device. Increased frontal activation in non-haptic trials may indicate a diminished presence experience.

4.2. EXPERIMENTAL PROTOCOL

The same experimental protocol used in Manuscript 1 was utilized for this experimental paradigm. Familiarization trials were provided before experimental trials to ensure participants understood the task, and knew that their target drill depth was 2 cm. A schematic of randomized trials presented throughout the experimental protocol can be found in Chapter 3 (Figure 1).

4.3. METHODS AND MATERIALS

4.3.1. Participants

Participants were volunteers recruited from the student population of Ontario Tech University, in Oshawa, Canada. Prior to any experiments taking place, all participants gave written informed consent. Five males and five females participated in the study for a total of 10 participants. Inclusion criteria included right-handedness and previous drilling experience. Due to excessive contamination of electrical noise, EEG data from one female participant and three male participants were removed from all statistical analyses. Participants that volunteered for this study were apparently healthy adults, aged 22.7 (± 1.4) years old, and self-reported normal hearing, and normal or corrected-to-normal vision (n = 6).

Participants completed pre-screening questionnaires before beginning the experiment. The Edinburgh Handedness Questionnaire was used to assess which hand was most dominant in each participant (right, left, or ambidextrous). Five participants reported right-handedness, while one participant was ambidextrous. An EEG safety checklist was also completed by participants prior to participation in the study. This was used to ensure participants did not have any pre-existing conditions that might impact the EEG data. Exclusion criteria could include a recent history of epilepsy, brain injury, or concussion, which could interfere with the interpretation of EEG signals.

4.3.2. Procedure

All experiments took place within the Neurophysiology and Human Rehabilitation Laboratory at Ontario Tech University in Oshawa, Canada. Only the participant, the student research lead, and one research assistant was present at the time of all experiments. Participants were seated on a chair in front of a desk, facing a

23-inch LG display monitor and the Novint Falcon haptic device. Seat arrangement was adjusted by asking participants to find a comfortable position facing the simulation monitor while grasping the Falcon. Participants were asked to get comfortable with the device by moving it through its range of motion. Distance from the participants' eye to the desktop monitor was measured (73.7 cm ± 3.7 cm), and external speakers were set up directly in front of the monitor, to ensure visual and auditory stimuli were spatially congruent. Before beginning the experimental trials, participants completed a familiarization phase to adjust to the force-feedback provided by the Falcon and practice drilling to 2 cm. During this phase, participants were able to see a side-view of the simulation, providing immediate visual feedback to ensure they could see how far the drill bit moved through the block of wood. Participants completed approximately 20 trials (50% with haptic force-feedback) before moving onto the experimental phase.

During the experimental phase, each participant completed a total of 200 trials. The first 100 trials were randomized, with 50 haptic trials and 50 non-haptic trials – this block was then repeated for a total of 200 trials. Three- to five-minute breaks were allotted every 50 trials, or upon the participants request. During these trials, the visual feedback provided during familiarization was removed, so participants could only view the front-view of the simulation. In both conditions, auditory stimuli were consistent. Images of the displayed simulation can be found in Chapter 3 (Figure 2).

4.3.3. Experimental Sequence

1. Drilling Simulation

As described in Chapter 3, the drilling scenario was developed from previous research by Melaisi and colleagues (Melaisi et al., 2018), and was created using the Unity game development platform by Unity Technologies. The low-fidelity Novint Falcon was used as a controller that provided force-feedback during this study (Figure 1). A mock-drill attachment was 3D-printed for the Falcon, ensuring the device light-weight, more similar in mass to a surgical drill. This was designed to reduce the impact of strength differences between participants.

The task itself was to drill 2 cm into a block of wood, with half of the trials providing the user with force-feedback, and the other half of trials without feedback. While the drilling environment and the block of wood was computer-simulated, users were able to operate the mock-drill and Falcon in place of a real drill. The researcher started each trial by pressing the Falcon's main button, and participants grasped and pushed the drill attachment to their perceived 2 cm depth, and returned the device back to its starting position. Real drilling audio recordings were played throughout the simulation, and indicated when the drill initially made contact with the wood.

2. Auditory Stimuli

The drill audio recordings were produced from a Stanley Black and Decker drill. Two different audio recordings were used during every trial: drilling in air as a baseline stimuli, and drilling through wood once the drill made contact with the block of wood. To limit external noise and reverberation of the generated sounds, all recordings were made in an audiometric room. When a trial began, the "air" drill recording played. Once the head of the drill bit made contact with the block of wood, the "air" recording stopped and the "wood" recording began. This recording was looped to play throughout the drilling movement. In this paradigm, the audio is synchronized to the user's movements, although the recordings did not change with altered pressure from the user, nor with the depth of the material. Based on previous research, this sound effect is commonly used in simulations of this nature (Melaisi et al., 2018). Frequency changes such as the ones described would be time-consuming, and may not be necessary for simple simulations such as the one presented in this study. Auditory stimuli were presented from external Sony speakers, presented at the same volume for all participants.

3. Haptic Stimuli

The Falcon provided force-feedback once the drill bit made contact with the block of wood in the simulation. Haptic stimuli were only presented during haptic trials. The “wood” audio recording and the haptic force-feedback were synchronous with the user’s movements.

4.3.4. EEG Data Acquisition

Continuous surface EEG was recorded using a Waveguard™ 64-electrode EEG cap (ANT Neuro, Netherlands) during trials with and without haptic force-feedback. All recording electrodes were referenced to CPz. The EEG cap was connected to the eego™ mylab amplifier (ANT Neuro, Netherlands) to collect each session at a sampling frequency of 1,024 Hz. Electrical impedance between the scalp and each electrode was adjusted to <10 kΩ using conductive EEG gel. ERD analysis was completed on a separate personal computer using Matlab™ (Natick, Massachusetts, USA). Statistical testing was done using SPSS version 24 (Armonk, New York, USA).

4.4. DATA ANALYSIS

4.4.1. EEG Analysis

All EEG data were visually checked for artifacts, and any artifacts representing eye blinks or muscle activity were selected and removed using Advanced Source Analysis software (ASA™; Netherlands). Raw EEG data were filtered with a 70 Hz low-pass filter and a 1 Hz high-pass filter. As prior research indicates, nine electrodes were relevant to ERD analysis in sensorimotor paradigms (Alegre et al., 2002), and included: frontal left (F3), frontal midline (Fz), frontal right (F4), central left (C3), central midline (Cz), central right (C4), parietal left (P3), parietal midline (Pz), and parietal right (P4). These electrodes were pooled into three regions of interest, which include: frontal (F3, Fz, F4), central (C3, Cz, C4), and parietal (P3, Pz, P4). A schematic can be seen in Figure 7.

Low alpha (8-9.5 Hz), high alpha (10-13 Hz), low beta (13-21 Hz), and high beta (21-30 Hz) frequency bands were isolated in spectral analysis. ERD analysis was performed using the band power method, as described by Pfurtscheller and Da Silva (1999). A fourth-order Butterworth band-pass filter was applied to isolate EEG signals into the previously mentioned frequency bands of interest. All amplitude data were then squared to obtain power samples, then averaged across all trials of the condition. This process was repeated twice for each participant – once for the haptic condition, and once for the non-haptic condition.

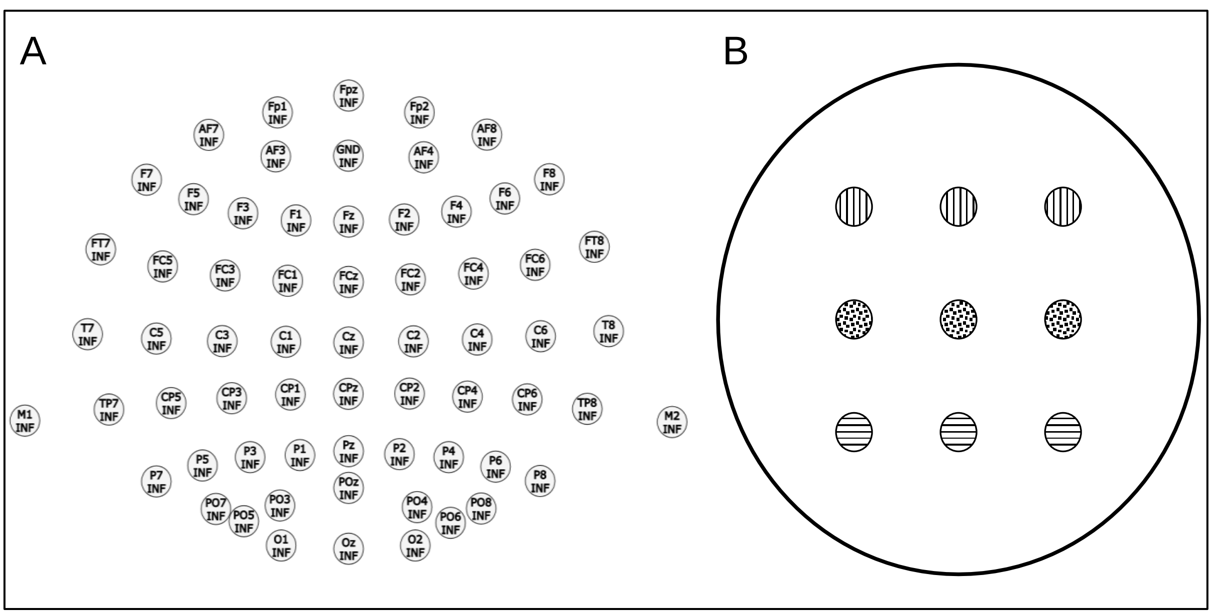

Figure 7. Electrodes of interest. (**A**) 64-electrode montage of the EEG cap by ANT Neuro. (**B**) Nine electrodes for ERD analysis, separated by brain region: frontal (vertical lines), central (grey dots), and parietal (horizontal lines).

The changes in band power were calculated as follows (Pfurtscheller & Lopes da Silva, 1999):

$$\text{ERD/ERS \%} = \frac{(\text{active band power} - \text{baseline band power})}{(\text{baseline band power})} \text{ X } 100$$

Note that negative values indicate a relative decrease in power (ERD) and positive values indicate a relative power increase (ERS). Since ERD represents a decrease in power, and ERS demonstrates a power increase, it is more precise to follow this expression (Pfurtscheller & Lopes da Silva, 1999). ERD/ERS data were calculated at each of the electrodes of interest and used for statistical analyses.

A basic element of measuring ERD/ERS is the EEG power (within specific frequency bands) post-stimulus displayed relative to the referential, or baseline power (Pfurtscheller & Lopes da Silva, 1999). This is typically conveyed as a percentage change from baseline. Since event-related changes within the EEG need sufficient time to develop and recover, the epochs chosen for baseline (pre-stimulus) and active (post-stimulus) periods are critical for interpreting results. The baseline period should be recorded several seconds prior to the onset of the stimulus, especially when alpha band frequencies are of interest (Pfurtscheller & Lopes da Silva, 1999). Data for each trial were averaged into 10-second epochs, consisting of 5-seconds pre-stimulus and 5-seconds post-stimulus. The reference band power was averaged approximately two to four seconds prior to movement onset, while the active power was averaged zero to four seconds after movement onset.

4.4.2. Statistical Analyses

ERD was calculated in each frequency band of interest at each electrode within each region (frontal, central, parietal). Outliers beyond ± 2 standard deviations were removed prior to statistical testing. A 3 electrode (X3, Xz, and X4), by 3 region (frontal, central, and parietal), by 2 condition (haptic and non-haptic) mixed-methods analysis of variance (ANOVA), with repeated measures on the last factor, was conducted for each frequency band of interest. Condition was the within-subjects factor, while electrode and region were the between-subjects factors. Alpha was set at $p = 0.05$, and partial eta squared (η_p^2) values were reported for effect size, where 0.01 indicated a small effect, 0.06 as medium, and 0.14 as a large effect (Richardson, 2011). All statistical tests were run using SPSS version 24 (Armonk, New York, USA). All data was checked for normality using Shapiro-Wilk's test and sphericity using Mauchly's test.

4.5. RESULTS

4.5.1. Low Alpha Band (8-9.5 Hz)

Repeated measures ANOVA revealed a statistically significant main effect and a large effect size for Condition ($F_{(1,42)} = 8.79$, $p = 0.005$, $\eta_p^2 = 0.17$). Figure 8 shows the mean and standard error of the mean (SE) of ERD during the haptic and non-haptic conditions. These results demonstrate a greater desynchronization in the haptic trials (-45.4% ± 3.1%) compared to the non-haptic trials (-41.5% ± 3.6%). As there was no interaction effect of Electrode, data was pooled across each region. Figure 9 displays the mean and SE of desynchronization across the frontal (n = 18), central (n = 15), and parietal (n = 18) regions for each condition. These findings seem to show greater desynchronization in the frontal, central, and parietal regions. A complete list of ANOVA results can be found in Table 1A, where significant findings are bolded.

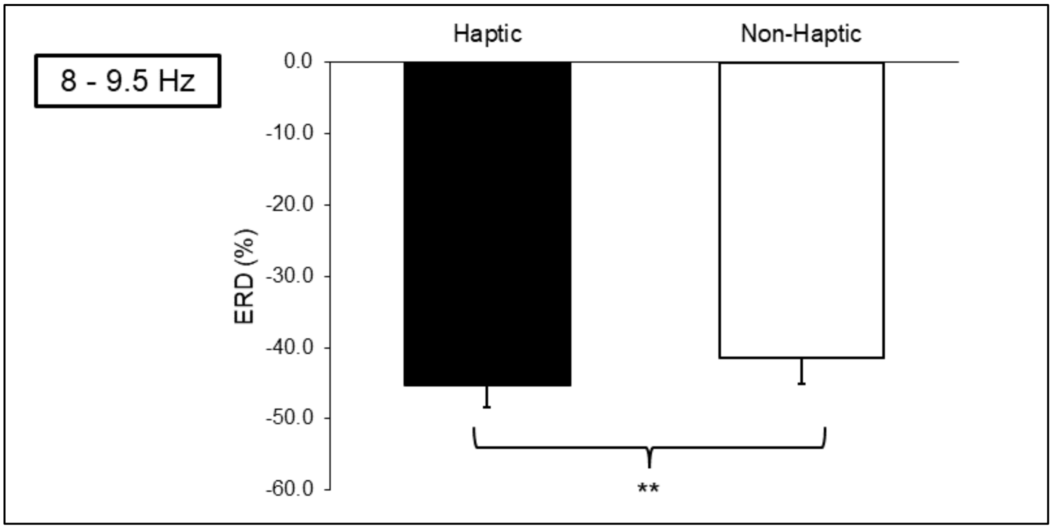

Figure 8. Low alpha band results. Mean and SE of ERD in haptic and non-haptic conditions. Statistical results are noted as *p<.05, **p<.01, and ***p<.001.

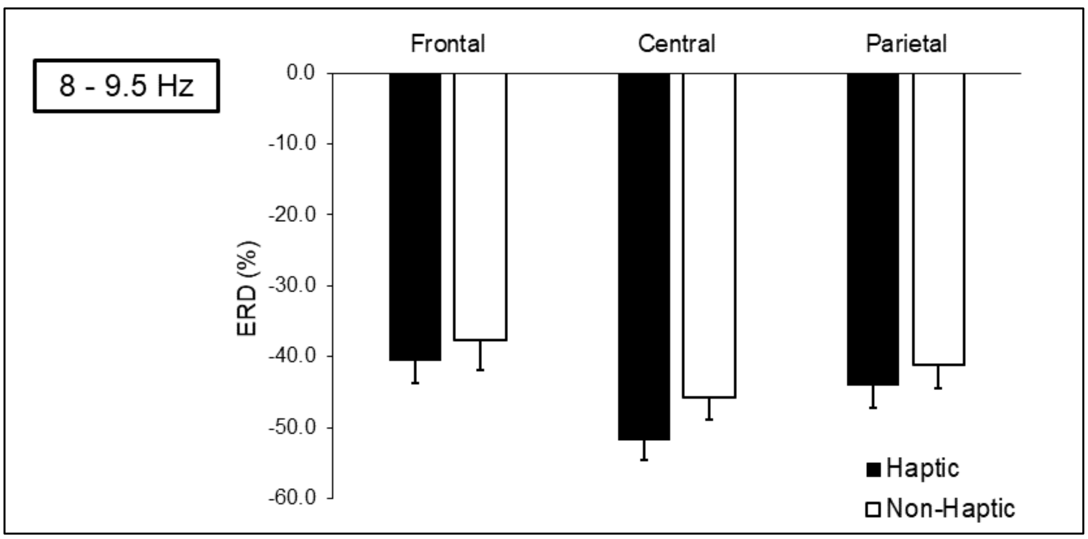

Figure 9. Low alpha band results. Mean and SE of ERD across frontal, central, and parietal regions in both haptic and non-haptic conditions.

4.5.2. High Alpha Band (10-13 Hz)

Mixed ANOVA revealed a statistically significant main effect and a large effect size for Condition ($F_{(1,42)}$ = 10.309, p = .003, η_p^2 = 0.19). Figure 10 shows mean and SE of ERD in both conditions. These findings imply there is a greater amount of desynchronization during haptic trials (-42.3% ± 2.7%) compared to non-haptic trials (-37.8% ± 2.9%). Electrodes were pooled across each region and graphed (see Figure 11) to demonstrate ERD across frontal (*n* = 18), central (*n* = 18), and parietal (*n* = 15) regions in conditions with and without haptic feedback. These results may indicate greater desynchronization in central and parietal regions during haptic feedback, compared to trials without feedback. All ANOVA results can be found in Table 1A.

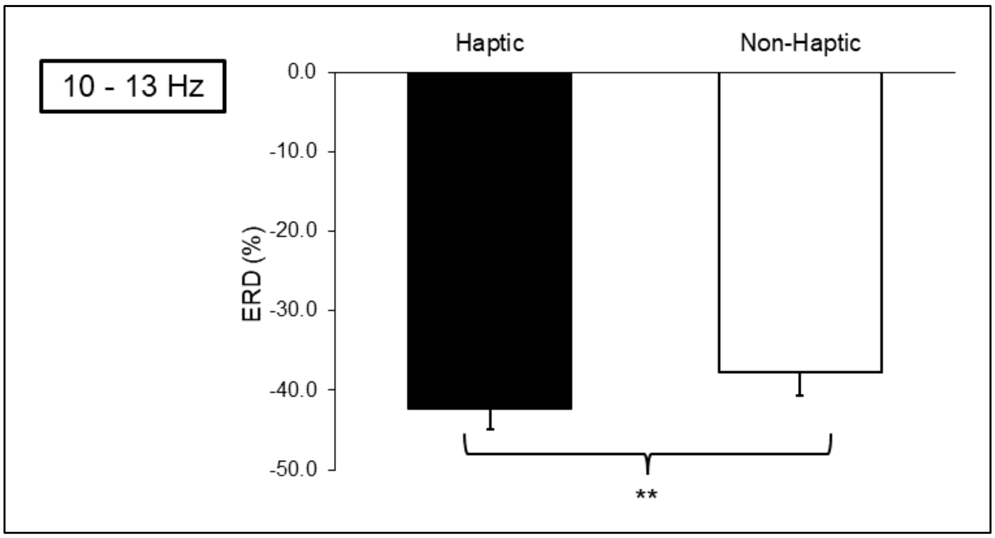

Figure 10. High alpha band results. Mean and SE of ERD in haptic and non-haptic conditions. Statistical results are noted as *p<.05, **p<.01, and ***p<.001.

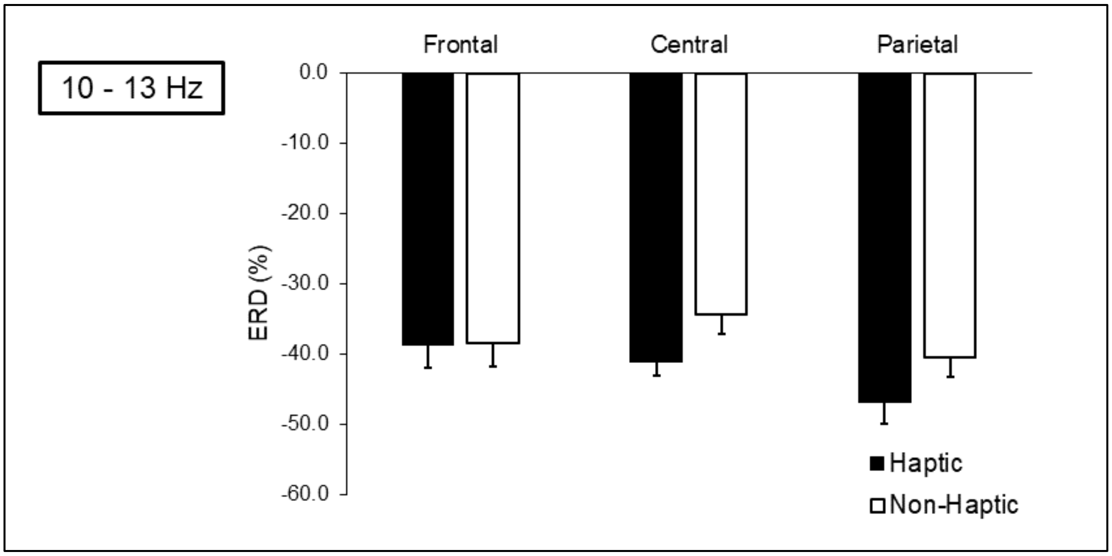

Figure 11. High alpha band results. Mean and SE of ERD across frontal, central, and parietal regions in both haptic and non-haptic conditions.

4.5.3. Low Beta Band (13-21 Hz)

Repeated measures ANOVA results demonstrate a small-medium effect size for Condition in the low beta band ($F_{(1,42)}$ = 2.179, p = 0.147, η_p^2 = 0.05). Figure 12 shows low beta ERD mean and SE in haptic (-28.0% ± 1.9%) versus non-haptic (-29.9% ± 2.4%) conditions. A medium effect size was revealed for the Condition by Region interaction ($F_{(2,42)}$ = 1.889, p = 0.164, η_p^2 = 0.08). Figure 13 displays ERD for haptic and non-haptic conditions over frontal (n = 15), central (n = 18), and parietal (n = 18) brain regions, when electrodes were pooled. These results may indicate greater desynchronization over frontal and central regions during the non-haptic condition. Low beta band ANOVA results can be found in Table 2A.

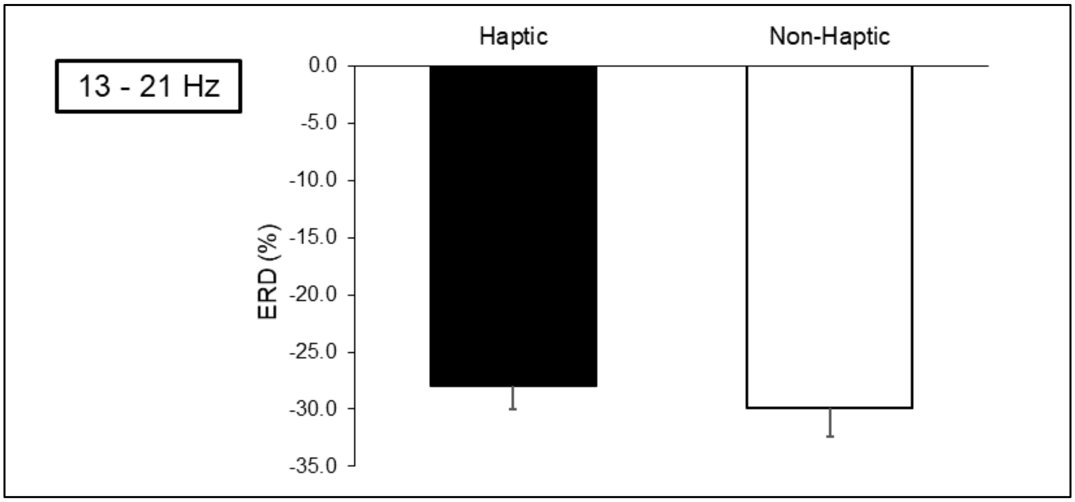

Figure 12. Low beta band results. Mean and SE of ERD in haptic and non-haptic conditions.

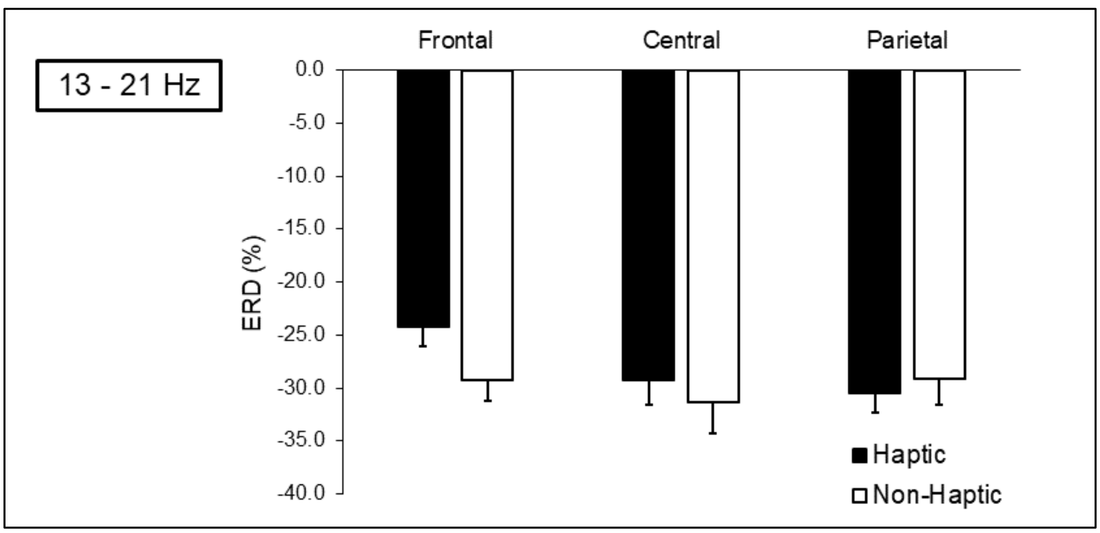

Figure 13. Low beta band results. Mean and SE of ERD across frontal, central, and parietal regions in both haptic and non-haptic conditions.

4.5.4. High Beta Band (21-30 Hz)

ANOVA results show a medium effect size for Condition ($F_{(1,33)} = 2.637$, $p = 0.114$, $\eta_p^2 = 0.074$). Figure 14 demonstrates high beta ERD in haptic (-23.7% ± 2.0%) and non-haptic (-22.0% ± 2.2%) conditions. A medium effect size was also found for the Condition by Region interaction ($F_{(2,33)} = 1.072$, $p = 0.354$, $\eta_p^2 =$

0.06). Figure 15 shows desynchronization in conditions with and without haptic feedback across frontal (n = 9), central (n = 15), and parietal (n = 18) regions. These findings may demonstrate greater desynchronization during haptic trials in central and parietal regions, consisting of electrodes over motor and sensory areas. High beta band ANOVA results can be found in Table 2B.

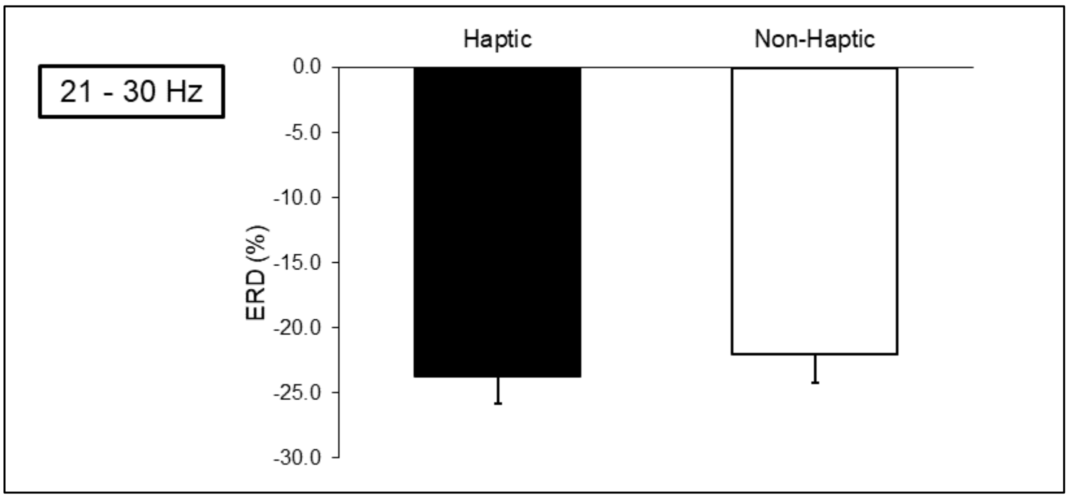

Figure 14. High beta band results. Mean and SE of ERD in haptic and non-haptic conditions.

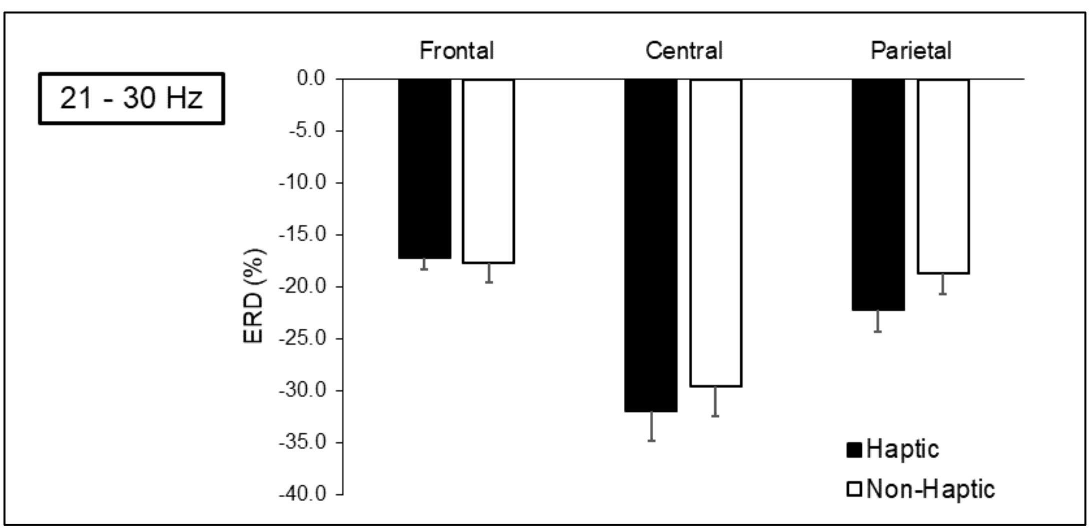

Figure 15. High beta band results. Mean and SE of ERD across frontal, central, and parietal regions in both haptic and non-haptic conditions.

4.6. DISCUSSION

As predicted, we found significantly greater desynchronization in trials with haptic feedback, as compared to trials without haptic feedback. It should be noted that due to unanticipated issues with electrical noise, we could only analyze the data of six participants, increasing the risk of type II errors. Additional data should be collected to confirm these findings and validate any existing trends within the data. This preliminary study found greater desynchronization during haptic trials in the lower alpha band (8-9.5 Hz) across frontal, central, and parietal regions, as well as in the upper alpha band (10-13 Hz) across central and parietal electrode clusters. There was no significant difference found between haptic and non-haptic trials in the beta band, although medium effect sizes indicate there may be greater levels of desynchronization during non-haptic trials in the low beta frequency band (13-30 Hz).

Desynchronization within the EEG signal is a known correlate of excited (activated) neural structures (Pfurtscheller & Lopes da Silva, 1999), and has been observed within specific frequencies during movement (Alegre et al., 2002; C.-L. Lin et al., 2012; Pfurtscheller & Aranibar, 1979), and during spatial navigation tasks (Baumgartner et al., 2006; Kober et al., 2012). However, previous studies addressing spectral power changes in VEs are often non-interactive and passive, largely focusing on the neural signatures involved in the spatial presence experience (Baumgartner et al., 2006; Kroupi et al., 2016). The visual scene is generally adapted to enhance presence in perceptual-based rendering paradigms, with less attention to auditory and haptic inputs (Baumgartner et al., 2008; Kapralos et al., 2017). While examining subjective presence is essential to the development of more immersive technology, it is necessary to explore how motor learning processes are influenced in multimodal simulations, in order to guide future recommendations for education and training purposes.

Recent work has illustrated altered cortical activation during a visuomotor task with haptic feedback, as compared to trials without feedback (C.-L. Lin et al., 2012). This work utilized a haptic joystick to perform a tracking task – while this may be a typical interface for motor learning paradigms, it may not be a realistic rendition of haptic feedback in the real world. Therefore, the current study was designed to explore differences in brain activation patterns between haptic and non-haptic trials of a simulated drilling task, using a 3D-printed mock drill as the haptic interface.

Lower alpha frequency desynchronization has been found in widespread areas over the scalp, and is thought to demonstrate general task demands related to attention (Pfurtscheller & Lopes da Silva, 1999). This phenomena seems to be supported by our initial findings, which demonstrate alpha band desynchronization across electrode clusters in frontal, central, and parietal regions. Furthermore, greater levels of desynchronization were found during haptic trials, which may indicate greater attentional processes are involved with the processing of multimodal stimuli. Lin and colleagues (2012) also demonstrated an alpha power decrease over central (motor) and parietal areas during a visuomotor task with haptic feedback. In the current study, significant differences of ERD in the upper and lower alpha band were found between trials with and without haptic feedback – the enhanced desynchronization occurring in haptic trials could be due to the additional sensory input provided by the haptic device, requiring different processing strategies as compared to the trials without haptic feedback. This may be the case when observing the enhanced ERD over central and parietal electrode clusters, areas known to be involved in multisensory integration and sensorimotor processing (C.-L. Lin et al., 2012; Molholm et al., 2006; Pfurtscheller & Lopes da Silva, 1999). Activation in frontal regions is common in early stages of motor learning, as this area is known to be involved in decision making, attentional processing, and selection of voluntary movements (Deiber et al., 1997).

Beta frequency band desynchronization has been observed during passive and active movements, over cortical areas involved in sensorimotor processing (Pfurtscheller & Aranibar, 1979; Pfurtscheller & Lopes da Silva, 1999; Stancák & Pfurtscheller, 1995), and is likely associated with movement preparation (Alegre et al., 2002). Although there were no significant differences between conditions in the beta band, we discovered medium effect sizes which may indicate increased desynchronization in non-haptic trials, which should be explored with a larger sample size. This difference appeared to be more prominent across frontal electrode clusters, which may suggest increased cortical activation over this area. An explanation for this could be related to frontoparietal connectivity networks, where increased frontal activation modulates parietal activity; this connectivity has been found to be correlated with lower ratings of presence in prior research (Baumgartner et al., 2006; Kober et al., 2012). No difference was found between haptic and non-haptic conditions in the upper beta band (21-30 Hz), however, effect sizes indicate the possibility of greater desynchronization in haptic trials over central and parietal areas. Beta power suppression over the central motor area has been observed in motor learning paradigms, and seems to play a role in movement execution and online sensory monitoring (Pfurtscheller & Neuper, 2010). Our findings show involvement of central (motor) electrode clusters, which may be indicated by greater ERD during haptic feedback trials. Haptic feedback provides more sensory information for sensorimotor integration, and likely facilitates the acquisition of new motor skills, as Manuscript 1 demonstrated enhanced motor performance during the haptic condition as compared to the non-haptic condition.

Altered afferent input has been shown to have detrimental effects on motor learning and performance, demonstrating maladaptive (unfavorable) neural plasticity (Baarbé et al., 2018; Murphy et al., 2003). It is reasonable to believe that multimodal interactions in VEs have the potential to lead to both adaptive and maladaptive plasticity, indicated by changes in motor performance and underlying neural elements. Prior research has indicated that unimodal and multimodal feedback can be beneficial for motor learning, however, not all types of feedback lead to accurate retention of motor skills (Salmoni, Schmidt, & Walter, 1984; Schmidt & Wulf, 1997; Sigrist et al., 2013; Wulf & Shea, 2002). It is important to characterize the impact of multimodal interactions in VEs across a variety of tasks, in order to guide future development of immersive simulations for education and training.

More advanced forms of EEG analysis, such as independent component analysis, which is often used to decompose EEG signals into temporally independent components, might increase the sensitivity of our ability to differentiate the neural substrates of immersion. Correlational analyses between subjective ratings of reality, cortical activity, and motor performance could also be utilized to determine the relationship between these measures, and their ability to predict the impact of training in ISEs.

4.7. CONCLUSIONS

The current study examined differences in brain activation in both haptic and non-haptic trials of a simulated drilling task, by comparing ERD across multiple electrode clusters. The results indicate that haptic feedback has the potential to induce widespread low alpha band and localized high alpha band changes in multiple cortical areas involved in sensorimotor processing, although a larger sample size is recommended to ensure adequate statistical power to compare across different electrodes with a region.

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CHAPTER 5. THESIS SUMMARY

As multimedia and interactive technology advances, expanding the quantity and quality of human-machine interfaces (Culbertson et al., 2018; Frauenberger et al., 2004), it is essential to understand how different sensory modalities can influence motor learning and underlying neurophysiological processes, such as multisensory integration and sensorimotor control. Learning complex motor skills often requires repeated practice, which results in temporal and spatial enhancements of the performed skill (Willingham, 1998). Performance outcomes, such as movement accuracy and response time, are frequently measured to assess how different conditions can alter skill acquisition and motor learning properties. VR and other types of immersive environments are popular tools for entertainment, education, rehabilitation, and training, and can benefit a variety of populations, such as stroke survivors, individuals suffering from post-traumatic stress disorder, medical professionals, firefighters, and military personnel (Coles et al., 2009; Cox et al., 2010; Deutsch, 2009; Levin et al., 2015; Merians, Poizner, Boian, Burdea, & Adamovich, 2006; Siu et al., 2016; Webb, Vincent, Jin, & Pollack, 2015; Williams-Bell et al., 2015). Research involving haptic and auditory interactions has increased over the past couple of decades, likely due to increased technology use (Frauenberger et al., 2004; Kapralos et al., 2017; Melaisi et al., 2018). Spatial presence, a well-known phenomenon that describes the feeling of “being there” in a simulated environment (Witmer & Singer, 1998), has shown to be linked to several neural correlates, including increased desynchronization over parietal regions of the cerebral cortex, and decreased desynchronization over frontal areas (Baumgartner et al., 2008; Baumgartner et al., 2006; Jäncke et al., 2009; Kober et al., 2012). With this information, this thesis sought to assess how audiohaptic multimodal stimuli can influence motor performance, subjective ratings of reality, and associated brain activity during a simulated drilling task. Prior work has focused on simple response-type paradigms (Hecht & Reiner, 2009), high-fidelity haptic devices (Coles et al., 2011), non-interactive VEs (Baumgartner et al., 2006; Jäncke et al., 2009), and haptic feedback provided from controllers that are rarely used in real world scenarios (C.-L. Lin et al., 2012). Task-relevant haptic feedback was hypothesized to improve motor performance during tasks where haptic sensation is involved. This thesis consisted of two studies: the first of which examined the effects of haptic feedback on performance accuracy and subjective ratings of reality, while the second study utilized the same task to explore areas of brain activation during trials with and without haptic feedback. These studies were designed to expand our understanding of multimodal interactions in immersive environments, and gather fundamental information to inform the design and implementation of training-based simulations.

The first study demonstrated that haptic feedback enhanced motor performance in a drilling task, as compared to trials without haptic feedback. Absolute error demonstrated that participants drilled more accurately when exposed to trials with haptic feedback. This was an expected outcome, as haptic feedback can inform the user when contact with a material occurs, and may provide sensations which update the body schema with information necessary to complete the task. Constant error indicated that participants consistently under-drilled (did not reach the target) during the haptic condition, a phenomenon similar to the undershoot bias in goal-directed reaching and aiming studies (Elliott et al., 2004; Engelbrecht et al., 2003). This behaviour in aiming studies has been suggested to result from the optimization of speed, accuracy, and energy expenditure, and is far more beneficial than overshooting errors, which increases time and energy required to complete the task (Elliott et al., 2004). This also has real world implications, as overshooting a target during drilling could have serious consequences in a surgical setting as well as domestic and occupational drill use. Variable error results indicated that participants were less variable when drilling with haptic feedback, as compared to trials without haptic feedback. This finding indicates that the addition of haptic sensations improved performance consistency, which is important for skill transfer to real world applications.

This study also found that haptic feedback improved subjective ratings of reality, a quality associated with spatial presence (Kroupi et al., 2016). In previous work, increases in subjective presence ratings were often associated with specific cortical activation patterns (Baumgartner et al., 2006; Kober et al., 2012; Kroupi et al., 2014). Thus, the second study compared cortical ERD over regions associated with sensorimotor processing while participants performed haptic and non-haptic trials of the same drilling task. The second study found greater high alpha and low alpha ERD in trials with haptic feedback, as compared to trials without haptic feedback. Haptic feedback resulted in greater ERD in lower alpha bands across frontal, central, and parietal regions, while upper alpha band desynchronization was found across central and parietal areas. These findings may indicate that the additional sensory information provided during haptic feedback requires different processing strategies than the non-haptic condition. Haptic feedback induced greater desynchronization in alpha bands, which is similar to patterns of ERD observed in VR studies which focused on changes in spatial presence.

The findings of this thesis provide researchers with more information on how multimodal interactions can influence motor performance, experience of reality, and associated brain activity. Various upper extremity tasks rely on tactile and kinesthetic information in conjunction with the other senses (auditory, vestibular, and visual) – reaching and aiming movements, object manipulation and recognition, and repeated tool use are just a few examples. Haptic devices have been used in surgical training to replicate the mechanical properties of tissue during manipulation and arterial pulse palpation – these types of training-based simulations are utilized for student practitioners to develop foundational skills before interacting with real patients (Coles et al., 2009; Kapralos, Moussa, & Dubrowski, 2014). This process is designed to ensure adequate practice and proficiency in skill acquisition, with the hope that the learned skills will translate to successful real-world performance. The findings of this thesis suggest that haptic feedback is critical to accurate performance in certain types of tasks.

The studies presented in this thesis offer insight into how haptic sensations alter motor performance and brain activation during a simulated drilling task. The findings of the first study demonstrated that audiohaptic interactions may have a significant influence on performance outcomes, where participants made less errors when performing trials with both auditory and haptic stimuli, compared to auditory stimuli alone. In addition, participants subjectively rated the haptic condition as feeling more realistic than the non-haptic condition, indicating that the addition of kinesthetic sensation can influence how individuals perceived the task. The second study built on this using non-invasive electrophysiological measures of activated brain regions and found different alpha band activation in haptic trials. Taken together, the two studies of this thesis provide novel information regarding neural plasticity and motor learning adaptations in virtual environments. With the ongoing enhancements in immersive multimedia and the increasing use of simulations in rehabilitation and training, it is critical to identify possible neural signatures of a trained state, in order to prevent the occurrence of maladaptive behaviours, and future work should build on the findings of this thesis.

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CHAPTER 6. APPENDICES

APPENDIX 1: Data Tables

Table 1

Alpha Frequency Band ANOVA Results

A. Low Alpha Band (8-9.5 Hz)

Within-Subjects Effects

Source	Sum of Squares	*df*	Mean Square	*F*-value	*p*-value	η_p^2	Effect Size	Observed Power
Condition	387.95	1	387.95	8.79	**.005**	.173	L	.826
Condition * Electrode	9.09	2	4.54	.10	.902	.005	S	.065
Condition * Region	50.51	2	25.25	.57	.568	.027	S	.139
Condition * Electrode * Region	66.92	4	16.73	.38	.822	.035	S	.128
Error	1852.39	42	44.11					

B. High Alpha Band (10-13 Hz)

Within-Subjects Effects

Source	Sum of Squares	*df*	Mean Square	*F*-value	*p*-value	η_p^2	Effect Size	Observed Power
Condition	511.50	1	511.50	10.31	**.003**	.197	L	.880
Condition * Electrode	84.27	2	42.13	.85	.435	.039	S	.186
Condition * Region	219.57	2	109.79	2.21	.122	.095	M	.426
Condition * Electrode * Region	214.05	4	53.51	1.08	.379	.093	M	.310
Error	2083.93	42	49.62					

Note. df = degrees of freedom. Effect size: small (S), medium (M), or large (L).

Table 2

Beta Frequency Band ANOVA Results

A. Low Beta Band (13-21 Hz)

	Within-Subjects Effects							
Source	Sum of Squares	*df*	Mean Square	*F*-value	*p*-value	η_p^2	Effect Size	Observed Power
Condition	96.13	1	96.13	2.18	.147	.049	S	.303
Condition * Electrode	1.83	2	.92	.021	.979	.001	S	.053
Condition * Region	166.59	2	83.29	1.89	.164	.082	M	.371
Condition * Electrode * Region	186.84	4	46.71	1.06	.389	.092	M	.304
Error	1852.65	42	44.11					

B. High Beta Band (21-30 Hz)

	Within-Subjects Effects							
Source	Sum of Squares	*df*	Mean Square	*F*-value	*p*-value	η_p^2	Effect Size	Observed Power
Condition	59.36	1	59.36	2.64	.114	.074	M	.351
Condition * Electrode	.086	2	.043	.002	.998	.000	S	.050
Condition * Region	48.26	2	24.13	1.07	.354	.061	M	.222
Condition * Electrode * Region	9.31	4	2.33	.103	.981	.012	S	.069
Error	742.74	33	22.51					

Note. df = degree of freedom. Effect size: small (S), medium (M), or large (L).

APPENDIX 2: Participant Consent Form

RESEARCH ETHICS BOARD
OFFICE OF RESEARCH SERVICES

You are invited to participate in a research study entitled: ***Neurophysiological Measures of Haptic Feedback during a Simulated Drilling Task.*** This study has been reviewed by the Ontario Tech Research Ethics Board File #15042 and originally approved on December 7th, 2018.

This study is being conducted by **Dr. Bernadette Murphy and Dr. Paul Yielder**, in conjunction with MHSc candidate **Brianna Grant** from the Faculty of Health Sciences at Ontario Tech University, in Oshawa, Ontario, Canada. All researchers involved will have signed confidentiality agreements and completed the TCSPII tutorial on research ethical concerns.

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Purpose and Rationale:

Virtual reality (VR) simulations are increasingly popular tools for education and training, especially within the medical, rehabilitation, and first-responder fields. VR allows users to safely explore a variety of environments and situations that may be hazardous and unethical in the real world. With technology advancing rapidly, it is important that we understand how VR and immersive environments interact with our brains. While exploring a new environment, we utilize all of our senses to get an idea of what is in front of us. Our eyes, ears, nose, and even our skin and limbs, are constantly exposed to sensory information. Our brain is able to take in this information and filter it into something that makes sense to us. This process is called multisensory integration. Our brains are so efficient at processing multisensory information, that we are able to interact with a new environment almost immediately.

Research has demonstrated that audio (hearing) and visual (seeing) senses are particularly important for successfully simulating a task or environment in VR. Haptic technology, which has the ability to mimic force, vibration, and/or touch, may be a critical factor in enhancing the VR experience. However, little is known about how haptic devices interfere with multisensory integration and processing within the brain.

The purpose of this study is to explore the neurophysiological measures of haptic devices, and their effectiveness in enhancing the presence experience in a virtual simulation. We hope this study will give us a better understanding of how haptic feedback is involved with multisensory integration.

The research we are doing will consist of multiple conditions of a virtual drilling task. We will ask you to wear an electroencephalography (EEG) cap, which will be measuring your brain signals. The cap is painless and non-invasive. To measure physiological measures such as heart rate and breathing rate, we will fit you with an Equivital belt that will be secured around your chest. We will also have a galvanic skin response (GSR) sensor on your left hand. FEMALE PARTICIPANTS: please note we will ask you to wear a sports bra or an undergarment without metal/wire to the data collection session.

Information for Participants:

To do this research, we will need to collect some information on how your brain processes different sensory stimuli (audio, visual and haptic) during a virtual task. We will also ask you to complete some questionnaires, which will provide us with information on your handedness, general wellbeing, and how you feel during the trials. We will ask you to wear the EEG cap and Equivital LifeMonitor belt, and we will explain the experimental task and teach you how to operate the mock drill.

For this study, we are seeking university-aged individuals (18-35 years) to complete two lab sessions. In order to participate in this study, you must complete an eligibility checklist in conjunction with one of the researchers to ensure you are eligible to participate. This includes ensuring that you are **right-handed**, have **normal or corrected vision**, and don't have any conditions that could influence the EEG measurements. You will also be given a chance to review the details of the study and ask any questions you may have.

You will first come for a familiarization session which will take approximately 15 minutes, while the second session will take 2-3 hours. If you are a student enrolled in an approved Kinesiology course, you may also have the opportunity to earn 1% extra credit which can be applied to the eligible course (see attached list in Appendix C). If you are interested in this option, the investigator will provide you with additional information. If you are not interested in this option, or you are not a Kinesiology student, your participation will be recognized with a Tim Hortons gift card of ten-dollar ($10) value.

Your participation in this study is voluntary and you are free to decline taking part in this study. You may also withdraw from the study up until the end of the data collection session, without reason. This will in no way affect your academic progress. The information that may be shared will be held in strict confidence and discussed only with the research team. Questions about your rights as a volunteer can be made to the Compliance Officer at 905 721 8668 ext. 3693 or compliance@uoit.ca.

Measurement sessions:

Should you agree to participate, we will need you to attend TWO (2) sessions. You will first attend a training session, followed by the experimental session.

Training procedures:

- The familiarization session will be used as an opportunity to read the study's purpose and rationale. Should you have any questions or concerns about the protocol, please talk to the researcher. During this **15-minute** session, you will learn how to operate the Novint Falcon controller. You will complete several trials to familiarize yourself with the experimental task and the proper operation of the device.

Experimental procedures:

- The second session is the experimental session. We will be examining how different modalities of sensory input will influence the human brain, via the collection of EEG data using a 64-electrode cap. This cap is painless and non-invasive. The cap will go over your head and hair, and we will need to insert conductive jelly near the electrodes placed over your scalp. You may feel a cool sensation when the gel touches your scalp – we will help to wash away excess gel post-collection.
- We will set you up with the Equivital LifeMonitor belt, which will sit against the skin of your chest, with straps that go over your shoulders (much like a sport bra). This belt will be collecting non-invasive physiological data. We will also measure galvanic skin response (GSR), which indicates physiological arousal. The GSR sensor will be attached to your left hand, as well as your left middle and index fingers.
- The researcher will remind you how to properly manipulate the Novint Falcon controller.
- You will perform several tasks with the mock drill, and after completion of the study, we will ask you to answer some questions about how you felt during each condition. The experiment itself may take less than an hour; however, with the full set-up of the EEG cap and completion of the questionnaires, this entire session may take up to **2-3 hours**. You will be

encouraged to take short mental breaks if necessary, but walking about freely may be restricted.

Risks and Benefits:

There are minimal risks associated with this study. Participation will take approximately 3 hours. Some participants could experience anxiety or stress as a result of their responses to the questionnaires. If this happens to you, please discuss any discomfort or distress with the researcher(s).

The benefit of participating in this study is that you will learn more about how your brain and body react to different sensory inputs. You will also get to use haptic technology created by fellow UOIT students and researchers. Your participation in this study will help to develop future haptic devices used in conjunction with VR simulations. You will also be aiding our understanding of how the human brain processes actual and artificial sensory inputs – a fundamental aspect of future VR research.

Storage of Data/ Confidentiality:

If the information you provide is reported or published, it is done in a way that does not identify you as its source. There is a potential for the data from the study to be used as secondary-data at some point in the future, and as such we are providing the option for you to tick a box indicating that you give consent to include this data in future research. The data will be stored in a locked area at UOIT for seven years from the completion of the study, after which it will be destroyed. You are free to withdraw from the data collection at any time up until the end of the data-collection session. Taking part in this study is voluntary and your decision to take part in this study (or not) will in no way influence your academic progress or relationship with your Instructors or TAs. If you have opted for extra course credit as compensation, this information will be handled confidentially by the Faculty Research Development Assistant and your teacher will not be informed until your course is already complete.

Participant Concerns and Reporting:

If you have any questions concerning the research study or experience any discomfort related to the study, please contact the researcher, ***Brianna Grant*** at brianna.grant@uoit.net.

Any questions regarding your rights as a participant, complaints or adverse events may be addressed to Research Ethics Board through the Research Ethics Coordinator – researchethics@uoit.ca or 905.721.8668 x. 3693.

Thank you very much for your time and help in making this study possible. If you have any queries or wish to know more, please contact Dr. Bernadette Murphy, a Professor at the University of Ontario Institute of Technology, Faculty of Health Sciences, 2000 Simcoe St North, Oshawa, Ontario, L1H 7K4 email: Bernadette.murphy@uoit.ca.

***Please read the following before signing the consent form and remember to keep a copy for your own records if you wish. By consenting, you do not waive any rights to legal recourse in the event of research-related harm.**

1. I understand that taking part in this study is voluntary (my choice) and that I am free to withdraw from the study up until the end of the data collection session without a reason and that this will in no way affect my academic progress.
2. This consent form will be kept in a locked area in the Neurophysiology and Rehabilitation Research Laboratory at UOIT, Oshawa, Ontario for a period of seven years before being destroyed.
3. The data collected in this study will be coded so that it is confidential from the consent form and stored in a locked area at UOIT, Oshawa, Ontario for a period of seven years before being destroyed.
4. I have read and I understand the information sheet for volunteers taking part in the study. I have had the opportunity to discuss this study. I am satisfied with the answers I have been given.
5. I understand that I can withdraw any data I supply up to the completion of my final measurement session.
6. I understand that my participation in this study is confidential and that no material which could identify me will be used in any reports on this study.
7. I have had time to consider whether to take part.
8. I know who to contact if I have any side effects to the study.

I, …………………………………………..................... agree to take part in this research.

I give consent for the data from this study to be used in future research as long as there is no way that I can be identified in this research. (Tick one)	YES ○	NO ○
I give consent for this data to be used as secondary-data at some point in the future. (Tick one)	YES ○	NO ○
I would like to receive a short report about the outcomes of this study. (Tick one)	YES ○	NO ○

Signed ……………………………………………………..… Date ………………….............

______________________________ ______________________________

(Name of Participant) (Date)

______________________________ ______________________________

(Signature of Participant) (Signature of Researcher)

APPENDIX 3: Edinburgh Handedness Inventory

Edinburgh Handedness Inventory

Initials _________________ Participant ID_____________________

Date of Birth ___________________ Sex ___________________

Please indicate your preferences in the use of hands in the following activities by *putting + in the appropriate column*. Where the preference is so strong that you would never try to use the other hand unless absolutely forces to, *put ++*. If any case you are really indifferent put + in both columns.

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.

	Left	**Right**
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking Match (match)		
10. Opening box (lid)		
Total Checks:		
i. Which foot do you prefer to kick with?		
ii. Which eye do you use when using only one?		

APPENDIX 4: EEG Safety Checklist

Safety checklist:

The following questions are to ensure it is safe for you to complete this study. If you answer yes to any of the questions below, we may need to exclude you from participating.

QUESTION	ANSWER	
1. Do you suffer from epilepsy, or have you ever had an epileptic seizure?	Yes	No
2. Does anyone in your family suffer from epilepsy?	Yes	No
3. Do you have any metal implant(s) in any part of your body or head? (Excluding tooth fillings)	Yes	No
4. Do you have an implanted medication pump?	Yes	No
5. Do you wear a pacemaker?	Yes	No
6. Do you suffer any form of heart disease?	Yes	No
7. Do you suffer from reoccurring headaches**?	Yes	No
8. Have you ever had a skull fracture or serious head injury?	Yes	No
9. Have you ever had any head surgery?	Yes	No
10. Are you pregnant?	Yes	No
11. Do you take any medication or use recreational drugs (including marijuana)*?	Yes	No
12. Do you suffer from any known neurological or medical conditions?	Yes	No

Comments ____

____

Name ____

Signature _____________________________________

Date ________________________________

*Note if taking medication or using recreational drugs please read through the medication list on the next page to see if you use contraindicated drugs or medications. You do not need to tell the researcher which medications or drugs you use, unless you wish to. However, all researchers have signed confidentiality agreements and this information will not be recorded in writing, if you do wish to discuss this issue.

**Dr. Murphy will meet with participants who answer yes to this question to seek further information.

Medications contraindicated with magnetic stimulation:

1) Tricyclic antidepressants

Name	Brand
amitriptyline (& butriptyline)	Elavil, Endep, Tryptanol, Trepiline
desipramine	Norpramin, Pertofrane
dothiepin hydrochloride	Prothiaden, Thaden
imipramine (& dibenzepin)	Tofranil
iprindole	-
nortriptyline	Pamelor
opipramol	Opipramol-neuraxpharm, Insidon
protriptyline	Vivactil
trimipramine	Surmontil
amoxapine	Asendin, Asendis, Defanyl, Demolox, Moxadil
doxepin	Adapin, Sinequan
clomipramine	Anafranil

2) Neuroleptic or Antipsychotic drugs

A) Typical antipsychotics

Phenothiazines:	Thioxanthenes:
o Chlorpromazine (Thorazine)	o Chlorprothixene
o Fluphenazine (Prolixin)	o Flupenthixol (Depixol and Fluanxol)
o Perphenazine (Trilafon)	o Thiothixene (Navane)
o Prochlorperazine (Compazine)	o Zuclopenthixol (Clopixol and Acuphase)
o Thioridazine (Mellaril)	Butyrophenones:
o Trifluoperazine (Stelazine)	o Haloperidol (Haldol)
o Mesoridazine	o Droperidol
o Promazine	o Pimozide (Orap)
o Triflupromazine (Vesprin)	o Melperone
Levomepromazine (Nozinan)	

B) Atypical antipsychotics

Clozapine (Clozaril)	Quetiapine (Seroquel)
Olanzapine (Zyprexa)	Ziprasidone (Geodon)
Paliperidone (Invega)	Amisulpride (Solian)
Risperidone (Risperdal)	

C) Dopamine partial agonists: Aripiprazole (Abilify)

D) Others
Symbyax - A combination of olanzapine and fluoxetine used in the treatment of bipolar depression.
Tetrabenazine (Nitoman in Canada and Xenazine in New Zealand and some parts of Europe)
Cannabidiol One of the main psychoactive components of cannabis.
Regular Cannabis use more often than once per week and/or cannabis use in the past 4 days.
Regular use of other recreational drugs, or single episode within the past three weeks.