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Investigating the Transfer of Learning, Psychological, and Neural Effects in Immersive Virtual Reality

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To the Graduate Council:

I am submitting herewith a dissertation written by Logan Taylor Markwell entitled "Investigating the Transfer of Learning, Psychological, and Neural Effects in Immersive Virtual Reality." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Kinesiology.

Jared M. Porter, Major Professor

We have read this dissertation and recommend its acceptance:

Jared M. Porter, Matthew Miller, Julie Partridge, Jessica Kutz Fleming, Shalaunda Reeves

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(Original signatures are on file with official student records.)

Investigating the Transfer of Learning, Psychological, and Neural Effects in Immersive Virtual Reality

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Abstract

Achieving mastery or expertise requires a substantial amount of quality practice. Recent technological developments have introduced a novel approach to practice, virtual reality. Specifically, virtual reality offers a low-cost, customizable opportunity to practice while minimizing the risk of the individual. Given that some types of practice may not lead to the acquisition of a motor skill, or worse, lead to detriments of that skill, understanding the developing science of motor behavior in relation to virtual reality is imperative. The following literature review will begin with a brief historical account of the evolution of virtual reality. Next, some terms of virtual reality will be defined, and the technological characteristics will be introduced. Then, fundamental theories of transfer of learning and important variables which likely contribute to transfer of learning will be discussed. In the following section, the current understanding of virtual reality and motor learning will be explained. Research that has examined transfer of learning within immersive virtual reality will then be examined and discussions of the findings and limitations will be presented. Finally, to address the shortcomings, the following project was a two-experimental study to investigate the transfer of learning effects of virtual reality motor skill practice.

Keywords: extended reality; human learning; human performance; transfer of training; motor skill; motor behavior; motor learning

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Introduction

History of Virtual Reality

The historic development of virtual reality (VR) traces back to the first three-dimensional (3D) immersive simulator created in the 1960s (Heilig, 1962). Morton Heilig, a Hollywood cinematographer, created Sensorama to allow individuals to feel like they were “in” a movie and was initially developed into an arcade machine. This was a simulated experience in which participants could ride a motorcycle through Brooklyn with sensory stimuli such as audio, smell, and haptic feedback (e.g., tactile, kinesthetic), including the feeling of wind (Heilig, 1962). In 1968, Ivan Sutherland invented The Ultimate Display, which was considered the first head-mounted display (HMD) system and had a mechanical tracking system (Sutherland, 1968). Sutherland’s HMD was created following a visit to the Bell Helicopter company where Bell mounted infrared cameras underneath a helicopter and attached a camera to the pilot’s head equipment. As the pilot turned his head, the camera under the helicopter moved in sync with the pilot’s head equipment. Sutherland substituted the camera with a computer that allowed the system to track the user’s head position and orientation. This system was able to update the three-dimensional virtual images witnessed by the participant in the HMD by a computer system (Sutherland, 1968). Later, in the 1970s, Myron Krueger developed Videoplace, which instead of an HMD, captured the body figure of the user and projected it onto a screen with which the user could interact (Krueger et al., 1985). This shadow-like projection allowed for two or more users to interact in a two-dimensional virtual environment. Unlike previous virtual environment systems, Videoplace did not limit the user’s body movement since it was based on a projection onto a screen and no equipment needed to be worn. Krueger et al.’s (1985) Videoplace remained experimentally focused inside his lab where the interaction between humans and computers were investigated. Then, in 1982, the first flight simulator, Visually Coupled Airbone System Simulator (VCASS), was created by the US Air Force. The VCASS was originally developed to minimize flight costs and allowed a pilot to control a simulated flight through an HMD that was connected to the cockpit and computer (Kocian, 1977).

In the 1980s, commercially available VR systems emerged and led to the development of numerous technologies such as the NASA produced DataGlove, that captured movement and orientation of the fingers and hands and the DataSuit, which captured full body movement and projected it onto a screen (Cipresso et al., 2018). DataSuit was later used by film actors to provide realistic, fluid motions to animated characters in movies with computer-generated special effects. Additional commercially available technologies were developed following DataSuit and included a helmet display such as Eyephone and BOOM. These were stereoscopic display systems that provided quicker responses to movement compared to the HMDs and allowed for movement tracking of the arms (Cipresso et al., 2018). These advances led to the development of the Virtual Wind Tunnel by NASA, which was created to research and manipulate airflow in a virtual spaceship or airplane. Following this, the Cave Automatic Virtual Environment (CAVE) system was developed at the University of Illinois in 1992 (Cruz-Neira et al., 1992). The CAVE system requires a large amount of space as the user must be inside a room-size cube in which projectors are used to display the virtual environment on the walls. This expensive system is not commercially popular but is used within many research labs. CAVE systems have been used within engineering companies to test products (Ottoson, 2010), construction planning, aviation (Repperger et al., 2003), and human movement (Chen et al., 2014).

Today, the CAVE system has continued to remain primarily laboratory focused given the nature of its size and cost. More recently, VR systems such as HTC Vive, Oculus Rift, and Oculus Quest 2 have become commercially available. They have significantly improved the quality of the technology with numerous uses in a highly immersive and interactive environments. These headsets have a variety of uses, commercially (Hornsey et al., 2020), in sport (Abbatine, 2020), and in research (Radianti et al., 2020).

Defining Virtual Reality and the Characteristics

Virtual reality is defined as a form of technology that enables one or more users to interact in real time with a simulation of a real environment, using their natural senses and motor skills (Burdea & Coiffet, 2003; Gray, 2019). A distinct difference between VR and **augmented reality** (AR) is that AR is a technology that "modifies physical surroundings with superimposed virtual elements. This virtual layer, placed between the physical environments and the user, can add textual information, images, videos, or other virtual items to the person's viewing of physical environment" (Javornik 2016, p. 252–253). On the contrary, VR creates a novel virtual environment with which the individual can interact. In other words, AR allows the individual to see the real environment while simultaneously having virtual elements overlay that environment. Whereas VR is a created or recreated non-real environment.

Given the popularity and the rapid evolution of VR technology, the term VR has been used rather loosely and has included display types such as a laptop or tv screen as well as those with a large field of view, such as a CAVE or HMD. **Field of view** is defined as what the stable eye and stable head position can see, measured in degrees, at a given moment (Sherman & Craig, 2003) and fully immerse the user in the virtual environment. It is the angular width of the user's vision. A human's horizontal field of view, for example, can reach up to 180 degrees when looking forward. For instance, if a user is standing in a three-sided CAVE, the user's field of view is 100% when the user faces forward because everything that the user is seeing is within the virtual environment. However, if the user turned 90 degrees to the right and maintained a stable head position, the open side of the CAVE (i.e., the non-virtual side) would obstruct the view of the virtual environment and the field of view would be reduced. On the other hand, **field of regard** is the amount of space that surrounds the user with the virtual environment. That is, what an eye can see in the surroundings when the user is moving their head (Sherman & Craig, 2003). For example, in a three-sided CAVE, or other stationary displays, the field of regard is less than 100% because the user can see the physical environment without the screens. Whereas, in HMDs, the field of regard has an unlimited range of motion, and the field of regard is 100%. Regardless of where the user turns their head, the HMD virtual environment is displayed in front of their eyes.

In a recent systematic review of immersive VR within education, researchers noted there was a lack of consistent usage of commonly used terms in the VR literature, such as classifying a system as immersive for non-immersive VR (Radianti et al., 2020). This work has highlighted the need for all fields to consistently use these terms in order to fully understand how this technology can be appropriately applied. Across the research, there are three primary characteristics involved with VR technologies, those are: immersion, presence, and interactivity (Ryan, 2015; Walsh & Pawlowski, 2002). **Interactivity** is the degree to which users can modify the virtual environment in real time (Steuer, 1995). **Presence** is described as the subjective feeling of being in the virtual environment (Parsons et al., 2017; Witmer & Singer, 1998). Slater (2009) and Salter and Sanchez-Vives (2016) propose two important characteristics to consider experiencing presence. That is, plausibility, which is the understanding that the scenario is actually occurring, and place illusion, which is the illusion of “being there” within the virtual environment. Researchers have defined and used interactivity and presence similarly across research; however, differing perspectives of immersion exist (Radianti et al., 2020). These multiple perspectives can be broken down into a technological or psychological basis. The technological perspective considers immersion as the system’s technical capability that allows a user to perceive the virtual environment and carry out actions based upon the perceived stimuli (Salter & Wilbur, 2016). This includes the degree of field of regard, the display resolution and accuracy, the range of sensory modalities (e.g., visual, auditory, haptic, etc.), and the field of view within the surrounding environment (Slater & Wilbur, 2016). In comparison, the psychological perspective considers **immersion** to be a psychological state in which the user perceives “an isolation of the senses from the real world” (Witmer & Singer, 1998). That is, the amount the user feels insulated from the stimuli of the physical environment and submerged within the virtual environment. Given the similarities between the subjective view of immersion and the current definition of presence, the technological definition of immersion will be used for the purposes of this manuscript. Namely, defining VR system’s level of immersion objectively, based on the degrees of field of regard provided by the system. Given the recent development of VR technology that has led to a rise in popularity of commercially available systems as well as an increase in research, consistently defining VR systems based on the primary characteristics can be a useful way to maintain similar usage of the terms within the scientific literature.

To remain consistent, a similar VR criterion as Radianti et al. (2020) was followed by defining types of VR as immersive or non-immersive based on their technological attributes. Immersive virtual reality systems are categorized as those that allow the user to be fully immersed into the virtual environment meaning the field of regard is 360 degrees. These commercially available systems include low-quality HMDs, which use a mobile phone as the technology source (e.g., Samsung Gear, Google Cardboard), high-quality HMDs (HTC Vive, Oculus Rift, Oculus Quest 2), and enhanced VR (a combination of head mount displays with gloves or bodysuits; see figure 1). Enhanced VR, which has also been termed embodied VR, uses gloves or bodysuits in addition to the HMD to provide sensorimotor feedback to the user (Haar et al., 2021). On the contrary, non-immersive virtual reality systems are those in which the user can still recognize the screen or conventional graphics workstation, or less than a 360-degree field of regard. Non-immersive VR include systems such as a desktop and a Cave Automatic Virtual Environment (CAVE; see figure 2). Given the differences in the level of immersion between immersive VR and non-immersive VR systems, this separation allows for a more detailed examination between VR systems.

Transfer of Learning

Transfer of learning (sometimes called transfer of training) is prevalent in everyday life. Transfer occurs whenever previous acquired knowledge, abilities, or skills influence the learning of a new task. Specifically, transfer of learning has been generally defined by researchers as the "influence of prior learning on the learning of a new skill or the performance of a skill in a new context" (Magill & Anderson, 2021, p. 307). Ultimately, the test of effective training or practice of a skill in VR is the degree to which that skill learned in VR can be applied in a real environment. Three primary characteristics are important to consider for transfer of learning: direction, magnitude, and distance (Gray, 2020; Magill & Anderson, 2021). First, the direction of transfer can be positive, negative, or zero. Positive transfer occurs when the prior experience improves the performance of a skill in a different context or facilitates learning of a new skill. Negative transfer occurs when previous experience interferes or leads to the

Low Quality HMD High Quality HMD Enhanced VR

Figure 1. Immersive Virtual Reality Systems.

Desktop CAVE

Figure 2. Non-Immersive Virtual Reality Systems.

deterioration of the performance of a skill in a different context or the learning of a new skill. Zero transfer occurs when previous experience does not have an effect on the facilitation of a new skill or the performance of a skill in a new context (Magill & Anderson, 2021). Second, magnitude refers to the size of the prior experience effect, which can range from small to large (Gray, 2020). Third, distance refers to separation between the original task and the transfer task in regard to the psychological and physical demands (Gray, 2020). A task that is to be practiced in the future which is similar or nearly identical to a previously practiced task regarding the cognitive and motor skills required would be considered near transfer. On the contrary, a transfer task that is relatively dissimilar, psychologically or during the movement production, would be considered far transfer. Thus, when using VR as a form of practice or training, the ideal outcome for the performance of the task in the real environment would be a positive transfer of learning with a large magnitude.

As an example of the distance of transfer, consider a smart phone application developed to improve a baseball player’s baseball pitch recognition capability. The baseball player watches different pitches within the application and quickly and accurately selects that pitch type. To measure pitch recognition performance, the number of correct answers can be assessed before and after pitch recognition practice using the same exact application. This illustrates near transfer because the evaluation task is very similar (or identical in this case), with respect to the cognitive and motor demands, to the task performed during the pitch recognition practice. When the practiced task is very similar to the transfer task, a significant improvement is typically observed (Abernathy & Wood, 2001). Research examining transfer of learning has shown that near transfer is almost always positive in direction and results in a large magnitude (Schmidt & Lee, 1982). Therefore, the effectiveness of using VR technology to improve skills within a real environment should be determined based on a demonstration of positive, far transfer of learning. In the pitch recognition example, evaluating far transfer of learning could be done by assessing the player’s pitch recognition capability during live batting practice before and after the intervention with the pitch recognition application.

Transfer of Learning Explanations

Ecological Psychology. Although several explanations have been proposed over the years for the positive transfer of learning effect, the transfer effect in a VR context has primarily been explained through an ecological psychology perspective. Through this lens, the behavior between the performer and the environment is viewed as a complex system. In general, the control of an action is thought to depend on the continuous interaction and the constraints imposed by the individual (e.g., physical and psychological characteristics), task (e.g., rules and equipment), and environment (e.g., socio-cultural, weather, light; Chow et al., 2011; Newell, 1986). Subsequently, to achieve optimal learning conditions, effective training conditions need to include these constraints to allow performers to discover a solution to solve the movement problem (Araujo & Davids, 2011). Representative learning design (RLD) is a method that been proposed to highlight these important constraints to help guide effective practice design and maximize transfer of learning (Brunswik, 1956; Pinder et al., 2011; Vilar et al., 2010). RLD suggests that *action fidelity* and *functionality* are critical to maximize transfer from one environment to another (Pinder et al., 2011). Action fidelity refers to similarities that exist between the individual’s actions or behaviors between the practice and test environment (Araujo et al., 2007; Stoffregen et al., 2003) whereas functionality refers to the similarities of the information between the environments in which individuals base their decision making and actions (Pinder et al., 2011). Taken together, maximizing the functionality and action fidelity enhances the representativeness of a learning environment and thus it is predicted to lead to greater transfer of learning (Araujo et al., 2007; Pinder et al., 2011; Stoffregen et al., 2003).

Information Processing. In addition to explaining transfer of learning through ecological psychology approach, transfer has also been explained through a cognitive psychology perspective for over a century. Through a traditional information processing lens, there have been two theories that dominate the literature: the elements theory (Thorndike, 1914) and the transfer-appropriate processing theory (Lee, 1988). Both theories recognize that to observe positive transfer of learning there must be similarities between the two situations, such as overlap between the skills or the context in which the skills are performed. However, the elements theory proposes that a positive transfer occurs due to the similarities between the movement components of the skill, such as the swing of a leg during a kick, and/or the environmental context in which the skill is performed (Thorndike, 1914). The transfer-appropriate processing theory proposes that similarities between the types of learning processes required is the reason for a positive transfer of learning (Lee, 1988).

Thorndike (1914) proposed the identical elements theory, later developed into Singley and Anderson’s (1989) identical productions model, which has roots in some of the earliest motor learning research. The “elements” are the general characteristics of a skill or the context characteristics in which a skill is performed (e.g., purpose of the skill), or the specific skill characteristics (e.g., movement components of the skill). This more traditional view of positive transfer suggests that positive transfer of learning is based on the similarities between the component characteristics or parts of two skills or the contexts of the performance. In this perspective, when two motor skills share common movement characteristics there will be greater positive transfer of learning between those skills (Thorndike, 1914). For example, predictions based on this theory would suggest a greater amount of transfer between an overhead tennis serve and an overhead volleyball serve compared to an overhead tennis serve and an underhand racquetball serve due to the shared similarities between the movement characteristics of an overhead tennis and overhead volleyball serve.

The second hypothesis, Lee's (1988) transfer-appropriate processing theory, proposes that positive transfer of learning occurs due to the cognitive process similarities that exists between two skills or performance scenarios. This suggests that while similarities between the components of the skill and context contributes to the transfer effect, this does not account for the full effect. Rather, the cognitive processing characteristics that are shared between two motor skills or performance situations influence the transfer of learning (Lee, 1988). It can be expected that the amount of learning transfer is related to the degree of similarity that exists between two skills and performance contexts in addition to the cognitive processes required. For example, shooting a basketball free throw inside an arena without any spectators creating psychological pressure, has different cognitive processing characteristics compared to a scenario shooting a free throw during a basketball game inside an arena filled with thousands of fans. It would be expected that a basketball free throw practice environment that can elicit the psychological pressure from noise, via spectators or fake crowd noise, would facilitate a greater positive transfer to the game environment compared to an empty, noiseless arena (Markwell et al., 2022). Evidence from testing the transfer-appropriate processing hypothesis and the identical elements theory suggest that there is merit to both (Lee, 1988; Thorndike, 1914). Thus, it can be expected that the amount of positive transfer of learning between two skills or environments is related to the shared similarities of the skill characteristics, environmental context, and cognitive processes. Taken together, both theories propose that to achieve positive transfer of learning, similarities must exist between the practice and transfer conditions (e.g., practice specificity; Proteau, 1992; Proteau et al., 1992).

In sum, regardless of whether transfer of learning is viewed through an ecological or cognitive psychological perspective, it is clear that both frameworks posit that by increasing the similarities between the performed task, the environment in which the task is learned, and the available information, transfer is enhanced from one environment to another (Araujo et al., 2007; Lee, 1988; Pinder et al., 2011; Proteau, 1992; Stoffregen et al., 2003; Thorndike, 1914). Thus, if such conditions are met within a VR context, it would be expected to observe transfer from a virtual to physical environment.

Fidelity

When understanding effective transfer, fidelity is an important consideration, at least to the level that it aids in positive transfer of learning (Gray, 2019; Harris et al., 2020a). Fidelity is the extent to which a real world (RW) scenario is recreated in a simulation, in terms of appearance in addition to the behavioral, cognitive, or affective states it elicits (Gray, 2019). While a sufficient level of fidelity is necessary to facilitate effective transfer of learning, the fidelity of VR should be assessed in relationship to the goal (Gray, 2002). For example, a VR system that is used to improve a motor skill (e.g., golf swing) would require the involvement of the realistic actions, however the realistic ergonomics might not be necessary for a VR system that is designed to improve the performance of a cognitive task. To better understand and test fidelity within virtual environments, Harris et al. (2020a) outlined a framework that highlights four types of fidelity to consider: physical, psychological, affective/emotional, and ergonomic/biomechanical.

Physical Fidelity

Physical fidelity is the extent to which the level of realism of the physical elements within the virtual environment is provided by VR (Gray, 2019; Harris et al., 2020a). These physical elements primarily include visual information, including the field of view, and the realistic behaviors of the elements, such as adherence to the laws of physics and level of functionality. The physical fidelity is likely an important contributor to the feeling of presence (Slater, 2009), and will depend on the level of immersion. Although the term "high fidelity" might be used to describe a high level of detail within the virtual environment (e.g., the texture of the ground, the emotional expression of avatars, the colors of objects within the environment), the level of physical detail is only one of the elements. It is important to also consider how realistic the environment is. For instance, if the user is able to walk through the wall of a building in VR, the realism is reduced. Thus, a certain level of physical fidelity is needed for effective transfer, but there is likely a limit to how much physical fidelity is necessary. Given that only a subset of information is used during an action (Davids et al., 2005; Williams et al., 1999), the inclusion of highly detailed information is likely irrelevant in terms of its use in facilitating transfer of learning. There is also a potential downside to a high degree of physical fidelity at the cost of potential lags in the VR system that might be introduced (Gray & Regan, 1999). Thus, understanding the appropriate level of physical fidelity is important for effective transfer.

Measuring presence is one method that has recently been used to determine a sufficient level of physical fidelity (Harris et al., 2020c). While this is an indirect measure, high levels of presence would suggest that the virtual environment is believable (i.e., plausibility) and leads to the feeling of "being there" (i.e., place illusion). Additionally, presence seems to influence the level of engagement during VR use as well and has been measured by self-report (Usoh et al., 2000), heart rate, eye-tracking, and electroencephalography (EEG) (Jennett et al., 2008; Nacke & Lindley, 2008). However, the influence of presence to benefit learning, independent of the enhancement of engagement, is yet to be determined (Fowler, 2015; Gray, 2019).

Psychological Fidelity

Psychological fidelity, on the other hand, is the extent to which VR replicates the perceptual-cognitive demands of a real task (i.e., the task performed in the real world) and leads to behaviors like those observed by the user in the real environment (Gray, 2019; Miller, 1954). For example, a VR system simulating a surgical procedure with high psychological fidelity should result in similarities to the RW of the same procedure such as using the same perceptual information (Bideau et al., 2010), the same gaze behavior (Vine et al., 2014), and levels of cognitive demand (Harris et al., 2020c). For domains that place demands on perceptual-cognitive skills, such as surgery, sport, and the military, psychological fidelity might be one of the most important factors to consider for effective transfer given the evidence for specificity of practice (e.g., Proteau, 1992). However, few studies have directly investigated the use of VR for perceptual-cognitive skill development, like anticipation or control of attention (Harris et al., 2020b; Tirp et al., 2015).

Methods of testing psychological fidelity have included comparisons of mental effort and gaze behavior between VR and real environments. Vine et al. (2014) examined differences in gaze behavior between simulated and real surgical procedures. They found that the expert surgeons made shorter duration and more frequent fixations in the real task compared to VR, suggesting less efficient visual control. The authors proposed that the stress of the RW operation, as well as the additional visual and auditory distractions contributed to the differences between tasks (Vine et al., 2014). Comparisons of physical and mental demands between the VR and RW task have also been investigated to evaluate psychological fidelity. For example, Harris et al. (2020c) investigated cognitive demands between the same task in VR and the RW, using a self-reported measure, the simulation task load index (SIM-TLX), to assess task load. These findings suggest that the cognitive demands were significantly higher in the virtual environment compared to the RW environment. Similar results have been shown in an experiment comparing cognitive load between immersive VR and non-immersive VR (Frederiksen et al., 2020). Frederiksen et al. (2020) found cognitive load, evidenced by secondary task reaction time, to be significantly greater in the immersive condition compared to the non-immersive condition. The level of cognitive load plays an important role for optimal learning as too much cognitive load could reduce the potential for learning (Guadagnoli & Lee, 2004; Kirschner, 2002). Thus, investigating psychological fidelity may require a combination of assessments to understand its impact on positive transfer of leaning.

Affective Fidelity

Similar to psychological fidelity, affective fidelity elicits a realistic emotional response from the user such as excitement, stress, or fear (Harris et al., 2020c). For scenarios that are high risk to practice in the RW like flying a helicopter at night over enemy territory or performing a life-threatening surgery, a high level of affective fidelity is required (Moghimi et al., 2016). For an emotional response to occur, this affective state relies on reaching the illusion of plausibility (Slater, 2009) as well as presence (Diemer et al., 2015). Research has shown that VR scenarios have successfully elicited emotional states similar to the RW (Chirico & Gaggioli, 2019). Given that stress inoculation training has been shown to be an effective method to enhance performance under stress (Saunders et al., 1996), the use of VR to elicit scenario specific emotional responses may provide significant benefits for the individual (Pallavicini et al., 2016).

Previous research to measure affective fidelity have used self-report psychophysiological measurements (Slater et al., 2016), alpha power from an EEG (Brouwer et al., 2011), skin conductance (Meehan et al., 2002), cardiovascular activity (Cosic et al., 2010), and a combination of physiological measurements (i.e., EEG, skin conductance, heart rate; Moghimi et al., 2020). Although there is some research examining methods to measure affective fidelity (Brouwer et al., 2011; Cosic et al., 2010; Meehan et al., 2002; Slater et al., 2006) in addition to examining how VR induces affective responses (Moghimi et al., 2016; Moghimi et al., 2020), little is currently known about how these VR-induced affective responses alter performance and learning (Harris et al., 2020c).

Ergonomic/Biomechanical Fidelity

Lastly, ergonomic and biomechanical fidelity facilitates realistic movements patterns in VR (Harris et al., 2020c). Although VR systems have significantly improved the level of haptic information provided to the user, the challenge to provide realistic haptic information still exists (Lopes et al., 2017). Furthermore, a lack of haptic information has also been shown to be an issue, disrupting motor control. As described by Harris et al. (2019), a lack of haptic information (Whitwell et al., 2015; Wijeyaratnam et al., 2019) in addition to poor depth perception, due to the vergence-accommodation conflict (Kramida, 2016) may significantly alter the current action of the task, potentially hindering transfer of learning. Depth perception has been one of the largest fidelity issues within VR (Gray, 2019). There has been consistent evidence of individuals underestimating the perceived distance (i.e., objects look closer than they really are) in non-immersive VR (Loomis & Knapp, 2003). Furthermore, evidence has shown less accurate depth perception and distance estimation while walking as well as reaching and grasping while in immersive VR compared to the real environment (Gonzalez-Franco et al., 2019; Mangalam et al., 2021). The magnitude of this effect has been shown to be quite large as well. Specifically, distance estimation errors in HMDs have been shown to be up to 50%. That is, if an object is recreated at a distance of 30 feet, the individual will see it as 15 feet. The vergence-accommodation conflict is a common explanation for this underestimation (Kramida, 2016). Based on the perceived location of an object, the rotation of the eyes (i.e., vergence) is adjusted, while the shape of the lens is adjusted to maintain a clear image over distance (i.e., accommodation) depending on the location of the object (Mon-Williams & Tresilian, 1999; Mon-Williams et al., 2001). While accommodation and vergence synchronously work together in a RW environment, a conflict arises in a virtual environment due to the object being presented at various depths while maintaining a fixed depth on a screen (e.g., ~5cm for HMDs; Eadie et al., 2000). Thus, given how this vergence-accommodation conflict can affect depth perception and ultimately behavior, biomechanical fidelity becomes an important consideration for how movement patterns are performed and acquired in VR and transferred to a physical environment.

Currently, minimal research has investigated biomechanical fidelity. However, the work that has been done suggests that low levels of biomechanical fidelity may be disruptive if the motor patterns reinforced by the VR task are too dissimilar from those required in the RW (Harris et al., 2020c). For example, Covaci et al. (2015) compared real basketball shooting to basketball shooting in VR. Specifically, this study examined differences in ball flight after the release in the RW and VR environment. Their results showed that the basketball shots made in VR had lower ball speed, higher height of ball release, and higher basket entry angle compared to the RW condition (Covaci et al., 2015), suggesting poor biomechanical fidelity. Bufton et al. (2014) compared three different VR table tennis games to table tennis in a RW environment. Their results showed that the VR table tennis groups produced faster and larger movements when hitting the ball compared to the RW environment. Similarly, Magdalon et al. (2011) compared reaching and grasping kinematics when picking up an object in VR compared to a real environment. This study found movements in VR were slower, had longer deceleration times, and wider grip apertures. These studies provide evidence that there are indeed biomechanical differences while performing a task in VR compared to a real environment. While these differences may lessen as the technology improve, further research is required to explore how these limitations impact RW learning as a product of VR practice.

Cognitive Processes

In addition to the fidelity related aspects proposed by Harris et al. (2020a), differences in the cognitive processes between RW and VR environments have also been questioned (Baumeister, et al., 2010; Kober et al., 2021; Wang et al., 2020). However, few researchers have yet to compare the brain activity involved in a VR environment to a RW environment. Among those who have, Baumeister et al. (2010) examined the cortical differences between a RW and VR environment while practicing golf putting using a Nintendo Wii. They found that putting in VR led to EEG differences compared to the RW environment, suggesting that practice in a VR environment may not replace a RW environment. Pacheco et al. (2017) compared brain activity during a lower limb motor task in a real and virtual environment. The lower limb motor task consisted of a stepping task on a Wii Balance Board for both conditions. During the VR environment condition, participants viewed a virtual game on a screen and attempted to make an avatar move up and down on the Wii Balance Board based on the auditory and visual feedback provided by the game. During the RW environment, the Wii Balance Board was used but the video game was turned off. Researchers used the same verbal instructions in both environments to guide the participants through the movement. Similar to the previous study, Pacheco et al.

(2017) found differences between the conditions. Specifically, the VR condition resulted in a lower alpha power compared to the real task.

Contrary to these findings, more recent work by Wang et al. (2020) and Kober et al. (2021) found EEG activity similarities between VR and RW conditions. Wang et al. (2020) showed that during a full body reaching task there were comparable changes in EEG power (decreasing alpha power and beta power) between the VR and RW environment. Furthermore, Kober et al. (2021) split participants into a RW group, a virtual group in which participants viewed realistic hands from a first-person perspective, and a virtual group in which the participants viewed an abstract version of hands from a first-person perspective. This study reported similar EEG activation patterns over the motor cortex between conditions during a block stacking task. However, revealed by the exploratory analyses, the abstract VR condition led to a weaker hemispheric lateralization effect compared to the condition in the RW. While, in general, there were similarities between groups, the abstract VR condition that was less realistic produced slightly more differences between the EEG patterns over the motor cortex when compared to the RW condition. Kober et al. (2021) also found that participants in the realistic VR condition reported higher measurements of presence compared to the abstract group. The authors proposed that this higher sense of “being there” might explain small cortical differences between the abstract and realistic VR conditions.

It's important to note that the studies that have shown large cortical differences between a task within a virtual environment and a RW environment (Baumeister et al., 2010; Pacheco et al., 2017) have used a Nintendo Wii, which is a non-immersive VR environment. Comparatively, the studies showing very minimal cortical activity differences (Kober et al., 2021; Wang et al., 2020) have used HDMs that provide a fully immersive virtual environment. The reason for these differences could potentially be due to the level of immersion. Other research supports these findings and have shown cognitive load differences when comparing the same task in an immersive environment to a non-immersive environment (Fredrickson et al., 2020). Similarly, self-reported measures of motivation and engagement have been shown to be different between immersion levels (Jung et al., 2011). These results provide additional evidence for the notion that the level of immersion may impact the cortical activity when a user is performing a task in a virtual environment. However, the extent to which this impacts transfer of learning remains unclear.

Taken together, it is evident that fidelity differences exist between tasks performed in VR and RW environments. Specifically, research has demonstrated these fidelity differences physically (Harris et al., 2019a), psychologically (Vine et al., 2014), biomechanically (Bufton et al., 2014; Covaci et al., 2015), and cognitively (Baumeister et al., 2010; Pacheco et al., 2017). Given that the primary goal of most of these studies was to investigate VR fidelity, transfer of learning was not typically assessed. It is important to note that without specifically assessing transfer of learning, one can only infer positive (or negative) transfer to RW environments from VR technology. This highlights the importance of previous research that has investigated the transfer of learning effects from VR practice.

Virtual Reality and Motor Learning

Despite decades of research investigating practice organization, it is still a matter of debate how practice can be best used to optimize the potential for motor learning (Bacelar et al., 2022; Cabral et al., 2022; McKay et al., 2022). What is clear, is that to achieve a level or mastery or expertise, individuals must dedicate a substantial amount of time to quality practice (Ericsson et al., 1993). Yet, designing practice can often be very costly, difficult to structure, and logistically complicated. Consider a baseball player who needs to practice hitting a knuckleball, a surgeon who needs to practice a specific procedure for an upcoming surgery, or a pilot who needs access to a helicopter to practice a complicated flight maneuver. Moreover, there is high risk involved considering the potential for human error or machine malfunction. The use of VR has gained interest as a method for overcoming some of these costly, risky, and complicated barriers (Michalski et al., 2019a). The evolution of immersive VR has created the potential for a low-cost method of practice that is affordable and commercially available. Additionally, this technology allows for the customization of the virtual environment, providing the opportunity to practice a skill within a specific scenario while minimizing the risk of the performer.

As technology has continued to rapidly evolve, many domains and professions have begun to incorporate VR as a tool to improve RW skills. One of the attributes this developing technology provides is the ability to generate a modified reality which allows behaviors to be practiced and assessed in a challenging, yet controlled and safe environment which may not be achievable in a physical setting (Levin et al., 2015). The potential opportunity to construct such an environment may allow for the unique development of optimal practice conditions using motor learning principles to facilitate a positive transfer of learning (Weiss et al., 2014; Wulf, 2007). Professions and domains such as firefighting (Stansfield et al., 2000), surgery (Seymour et al., 2002), aviation (Hays et al., 1992), and sports (Gray, 2017) have used this technology and shown benefits from practicing in VR. However, many studies that have examined the benefits of this technology have not examined transfer of learning. For example, Stansfield et al. (2000) used a VR based system designed to train emergency response personnel. The participants were firefighters with a variety of experience ranging from very little to more than 10 years. The firefighters participated in one of two simulated emergency scenarios (i.e., tension pneumothorax or head trauma) that required them to recognize the problem and address the specific symptoms. While this study found that participants were satisfied with the VR experience as a modality for first-responder training based on self-reported data, transfer of learning was not evaluated.

In the field of surgery, Seymour et al. (2002) was the first to validate the use of VR for surgical residents to improve operative procedure performance. Half of the surgical resident participants performed 10 gallbladder dissections with the Minimally Invasive Surgical Training-Virtual Reality (MIST VR) system in addition to the traditional training. The participants who used the MIST VR system completed the dissection 29% faster compared to the residents who only had traditional straining. Additionally, the participants who only had the traditional training were nine times more likely to fail to make improvements and five times more likely to injure the gallbladder. Overall, Seymour et al. (2002) demonstrated a positive transfer of learning in addition to hands on experience of gallbladder surgery without placing a patient at risk.

More recently, Gray (2017) investigated how high school baseball players could utilize VR to improve batting performance during their regular season. Eighty participants were assigned to one of four groups: adaptive training in VR, extra batting in VR, extra batting in the RW, or no additional batting practice. The adaptive training group increased the level of challenge as the batter improved, utilizing the challenge point framework (Guadagnoli & Lee, 2004). After training twice a week for six weeks, results showed that the adaptive training in VR group resulted in significantly greater improvements in RW performance (i.e., regular season batting average) compared to the other groups. Not only did Gray (2017) show how VR training can effectively transfer to RW performance, but this study also highlighted the potential benefit of VR systems that allow the environment to be created in a way that optimizes the practice structure to maximize motor learning.

While promising, and though companies developing VR technology may claim the RW benefits from training in a virtual environment, the current evidence supporting RW improvements from VR practice is quite limited. Some of the literature shows positive transfer from virtual to RW environments, whereas some studies show no transfer or even negative transfer (De Mello Monteiro et al., 2014; Demers et a.l 2021; Drew et al., 2020; Gray, 2017; Kozak et al., 1993; Levac et al., 2019; Michalski et al., 2019a; Szpak et al., 2019; Todorov et al., 1997). For example, Gray (2017), Kozak et al. (1993), and Todorov et al. (1997) all found that motor skills practiced in VR positively transferred to a real environment. On the contrary, experiments such as Drew et al. (2020), and De Mello Monteiro et al. (2014) reported no transfer of learning from VR to a real environment. A review investigating the use of VR in rehabilitation science found only a small number of studies investigated whether skills transferred from virtual to RW environments within healthy and neurological impaired individuals (i.e., Cerebral Palsy; Duchenne Muscular Dystrophy; Levac et al., 2019). Of the six studies reviewed, discrepancies in the success of transfer from virtual to real environments were found as four of the studies showed no transfer from a virtual to a real environment. Levac et al. (2019) proposed that methodological shortcomings, limited number of practice trials, and small sample sizes played a potential role in the inconsistencies found in the results of the studies reviewed. Other researchers conducted a systematic review and examined the effectiveness of VR as a tool to train sport skills (Michalski et al., 2019a). Though many claims have been made regarding the positive effectiveness of VR to train sport skills, Michalski et al. (2019a) found very little data to support RW improvements by training in VR. Studies were excluded from the review if they did not assess transfer to a sport in a real-environment, were not sport related, were not peer-reviewed, or did not report on the VR technology. Regardless of these inclusion criteria, five experiments that met their criteria (Gray, 2017; Rauter et al., 2013; Tirp et al., 2015; Todorov et al., 1997), did however, provide some support that closed skills are transferrable from VR to the RW (Michalski et al., 2019a). Specifically, all their findings suggested that VR improved RW performance compared to no training (Gray, 2017; Tirp et al., 2015) and three out of the five experiments showed the improvements in the RW were significantly greater following VR training compared to training in the RW. Lastly, Demers et al. (2021) conducted a systematic review of 26 studies which investigated the integration of motor learning principles during VR interventions within patients with Cerebral Palsy. This research found that while a few studies suggested the potential for skills acquired in VR to transfer to the RW environment (Golomb et al., 2010; Hernandez et al., 2018; Robert et al., 2013; Sandlund et al., 2014), the majority of the studies included in the review did not assess transfer from VR to RW environments (Demers et al., 2021).

In sum, the review by Levac et al. (2019) examined transfer of motor skills from a virtual environment to a RW environment. While Levac et al. (2019) proposed that VR provides the opportunity to understand how motor skills transfer from VR to a RW environment, the review did not find conclusive evidence to support that hypothesis. This is contradictory to the findings by Michalski et al. (2019a) as this systematic review investigated transfer within sport skills and found evidence of transfer for closed skills within non-immersive VR systems. Additionally, all the studies within Michalski et al. (2019a) provided evidence that VR improved RW performance compared to no training and most of the studies found VR improved RW performance greater compared to training in a physical environment. Taken together, these reviews across different domains provide some initial evidence that practice in a non-immersive VR environment appears to facilitate a positive transfer of learning to a RW environment in closed skills. Although, consistent with findings by Demers et al. (2021), it highlights a scarcity of the research and the need to further examine how skills performed in VR transfer to a RW environment.

Additionally, previous research on VR has shown that the classification of VR systems tends to be grouped similarly, disregarding levels of immersion (Radianti et al., 2020). However, vast characteristic differences, specifically with respect to the level of immersion, exist between types of VR systems. Perhaps these differences are a potential reason for the inconclusive evidence regarding motor skill transfer from a VR to RW environment. For example, previous researchers have shown psychological differences between immersion level and specifically found that a high degree of immersion has led to an increase in motivation and satisfaction with virtual environments (Jung, 2011). More recently, a study comparing reaching performance and quality of movement between non- and immersive VR, showed lower performance and hand trajectories in non-immersive VR compared to immersive VR, suggesting that motor behavior may also differ between levels of immersion (Gerig et al., 2018). Furthermore, the physical interference given the nature of the immersive VR systems, such as the position and weight of the headset and the large cables connecting to the headset, have been proposed as an issue that potentially hinders learning (Miles et al., 2013). It has been suggested that this possible learning hinderance could be due to a potential distraction from the cables, taking the user’s attention away from the task. Additionally, there could be a specificity issue where the user has learned the task while certain movements are constrained by the cables but then performs the task in a RW environment without the constraint of the cables (Miles et al., 2013). Given the behavioral and affective differences between immersive and non-immersive VR that have been observed during the performance of a motor skill, (Jung, 2011; Miles et al., 2013), as well as physical differences between immersive VR and non-immersive VR systems, it is possible that transfer of learning differences exist as well. Therefore, to fully understand how motor skill practice in VR transfers to RW environments, an examination of studies that have specifically investigated how immersive VR transfers to RW environments is imperative (Demers et al., 2021; Levac et al., 2019; Michalski et al., 2019a).

Transfer of Learning from Immersive VR to RW Environments

Recently, Michalski et al. (2019b) investigated motor skill transfer of learning from an immersive VR environment to the RW. In that study, participants (N=57) were assigned to either a VR group or a non-training control group. The VR group completed a total of three hours and 30 minutes of table tennis competition against an artificial opponent generated by artificial intelligence. The intervention was split across seven sessions, with no more than one session per day, and was recommended that the participants complete two sessions per week. While all participants performed seven sessions of practice totaling three hours and 30 minutes, the practice frequency and time per session were not controlled across participants. The participants used a table tennis application using an HTC Vive HMD. The control group did not receive any practice during the intervention phase. Performance was measured pre- and post-training by the number of successful returns of a backhand, forehand, and alternating stroke. Additionally, a qualitative skill assessment was performed. Experts observed the technique and consistency of the participants' serving. Paired samples t-test showed that both the VR group and the non-training control group significantly improved their RW tennis performance from pre- to post-test. The analysis also found no tennis performance differences between groups at the pre-test. However, an independent samples t-test showed the VR training group's RW tennis performance was significantly higher compared to the control group during the post-test. Similarly, their analysis revealed that the change in qualitative assessment scores were significantly greater in the VR group compared to the control. The results suggested that the VR group improved significantly more compared to the control group in both the quantitative and qualitative assessments. Additionally, a significant positive correlation was found between the quantitative and qualitative assessments. This study suggests that table tennis practiced in immersive VR can result in a positive transfer of learning to the RW and result in greater performance improvements compared to no practice at all.

Harris et al. (2020a) expanded these findings by conducting a two-experiment study to examine the transfer of learning effects of immersive VR when used as a warmup and investigating the effects of the participant's gaze behavior. In the first experiment, 18 amateur golfers were subjected to two blocks of 20 golf putts in immersive VR to act as a warmup. The pre- and post-test in a RW environment were immediately before and after the immersive practice. Putting accuracy and quiet eye duration were used to determine performance and gaze behavior, respectively. The results showed that there was no significant difference between putting performance at baseline and performance following the VR practice. However, there was a significantly higher radial error on the first putt following the practice in VR. Similarly, there was not a significant difference between quiet eye duration during the post-test compared to baseline. Although, there was a significantly higher reduction in quiet eye duration on the first putt compared to the average baseline. The results from the first experiment suggest that performance in immersive VR immediately prior to performance in the RW led to an impairment in performance and a disruption in quiet eye in the first putt but recovered by the second putt to a performance comparable to baseline. Thus, despite the appeal to use VR for warm up repetitions or as a preparation prior to competition, this experiment suggests that VR could have potential detrimental effects on performance and gaze behavior when used immediately before RW performance. Such findings are likely due to the slight haptic and visual differences between the virtual and real skill. Therefore, it should not be concluded that VR is beneficial in all cases. Furthermore, findings such as those reported by Harris et al. (2020a) suggest that individuals should be wary of using VR as a preparatory tool.

In the second experiment performed by Harris et al. (2020a), researchers examined whether practice in immersive VR would transfer to the RW environment in novice golfers. Forty novice golfers were assigned to a RW or a VR group. Participants practiced 40 putts in their respective groups. Pre- and post-outcome measures were putting accuracy (radial error) and quiet eye duration. Results showed that both groups significantly improved their putting accuracy in the RW post-test and were similar between RW (10.7%) and VR (11.9%) groups. Additionally, there were no significant differences in quiet eye duration between groups. Interestingly, only the VR group showed a significantly improved accuracy in the virtual environment. That is, the transfer of learning occurred from VR to the RW but not from RW to VR. In summary, a positive transfer of learning effect occurred within participants at an early stage of learning within minimal practice. However, there was no improvement in quiet eye duration, suggesting that perceptual skills may require a greater amount of time to develop compared to motor skills practiced in a VR context.

Following Harris et al. (2020a), Drew et al. (2020) examined how dart throwing practiced in an immersive VR environment immediately transferred to a RW environment. They randomized 41 participants into a VR group or a RW group. In both groups, participants completed 10 dart throws and rested one minute until they accrued a total of 100 throws. The pre- and post-testing occurred the same day, immediately before and after the practice session.

Task performance (i.e., throwing accuracy), perception (i.e., visual symptoms [acute symptom survey, VRSQ, CUS] and oculomotor behavior [accommodation facility and vergence facility]), and throwing kinetics and coordination were measured. Throwing accuracy for the RW group significantly outperformed the VR group during the posttest. Additionally, there was a significant effect of time on accuracy. That is, the VR group performed significantly less accurate and the RW group was significantly more accurate following the training. The VR group reported greater acute visual symptoms compared to the RW group during the posttest. However, oculomotor behaviors were similar between groups before and after training. During the practice trials, the VR groups exhibited different dart throwing kinematics, but the posttest resulted in non-significant differences. Based on this finding, Drew et al. (2020) suggested that the VR group had adapted their throwing pattern. However, while the throwing kinematics may have been similar during the posttest, throwing kinematics were different between groups during the practice and throwing accuracy decreased over time in the VR group and increased over time in the RW group. Additionally, while the oculomotor behaviors were similar between groups, the VR group reported more visual symptoms compared to the RW group. These results are similar to those in experiment one of Harris et al. (2020a) being that RW performance decreased immediately following practice in VR. This study highlights a couple important points. First, biomechanical fidelity was different in VR compared to RW practice and VR practice resulted in worse RW posttest accuracy. Second, of the two studies that have used immediate posttests to investigate the effect of VR practice on RW performance, both have resulted in decreases in performance. This finding highlights the caution to use VR as a preparatory tool and suggests that the transfer of learning effects from VR to RW may not be as simple as positive, neutral, or negative. Rather, it suggests that the timing at which VR is used, prior to RW performance, may also influence transfer of learning and more research is warranted to understand this effect.

Lastly, Oagaz et al. (2021) investigated performance improvement and motor skill transfer in table tennis using immersive VR. Specifically, the purpose of the study was to investigate how the practice of table tennis forehand and backhand returns influenced the number of returned balls, the returned ball's speed, and the returned ball's height during a retention test within a RW environment. Participants (N=18) were randomly divided into a VR group and a no training control group. In the VR group, participants practiced table tennis forehand and backhand returns using a VR application for five sessions that lasted 45 minutes each. Pre- and post-table tennis assessments were performed in the RW. The results showed a significant improvement in ball speed and height compared to the baseline assessment. However, no significant changes were found for the number of tennis balls returned. This study suggests that practice in immersive VR appears to be at least a partially effective method to facilitate a positive transfer of learning to the RW and shows that VR practice improved table tennis performance relative to no practice at all.

Summary and Future Directions

While there is evidence to support the conclusion that both non-immersive VR and immersive VR can effectively facilitate positive transfer of learning from a virtual environment to a RW environment, specifically within sport and rehab (Gray, 2017; Kozak et al., 1993; Michalski et al., 2019b; Szpak et al., 2019; Tirp et al., 2015; Todorov et al., 1997) other evidence suggests learning in VR does not transfer (Demers et al. 2021; Levac et al., 2019; Michalski et al., 2019a), and sometimes even hinders performance in a RW environment (Drew et al., 2020). Given the distinct differences between VR systems that are immersive compared to those that are not (Appelbaum & Erickson, 2018; Covaci et al., 2015; Miles et al., 2013; Szpak et al., 2019), it is important to understand whether tasks practiced in immersive VR transfer to the RW. Currently, very few studies have investigated whether motor skills performed in immersive VR transfer to a RW environment (Drew et al., 2020; Harris et al., 2020b; Michalski et al., 2019b; Oagaz et al., 2021). Of those studies, a positive transfer of learning from an immersive VR headset was partially supported (Harris et al., 2020b; Michalski et al., 2019b; Oagaz et al., 2021). Drew et al. (2020) found that dart throwing practice in immersive VR led to an impaired performance in a RW environment. However, the design of that study was slightly different given that the transfer test in the real environment occurred immediately following practice in immersive VR. Interestingly, the first experiment of Harris et al. (2020b) also found that when immersive VR was used immediately prior to the performance in a real environment, motor performance was impaired in addition to a disruption in quiet eye. However, these impairments were no longer observed by the second repetition, suggesting that these detriments can potentially be negated and therefore the use of VR as a preparatory tool could be effective. A similar study demonstrated negative visual and cognitive aftereffects, such as changes in accommodation as well as an increase in a decision-making reaction time task immediately following practice in immersive VR. Although, motor performance was unaffected (Szpak et al., 2019). While Szpak et al. (2019) proposed that the negative cognitive effects observed could be related to alertness and attention, further research is needed to understand why visual, cognitive, and motor performance has been shown to be negatively affected immediately following the use of immersive VR (Drew et al., 2020; Harris et al., 2020b; Szpak et al., 2019). Specifically, future investigations should manipulate the amount of time between a VR task and a RW task to further understand the impact these characteristics have on transfer of learning from a virtual to real environment.

One factor that the studies reviewed herein have in common is the skill level of the individuals. All of the studies summarized in this review that support positive transfer of learning from an immersive VR environment to the RW were conducted with a novice population (Drew et al., 2020; Harris et al., 2020b; Michalski et al., 2019b; Oagaz et al., 2021). However, based on the current evidence, it is not clear how skills practiced in immersive VR transfer to a real environment within moderately or highly skilled populations. The skill level and the difficulty of the task are critical components to optimize motor learning (Guadagnoli & Lee, 2004). The challenge point framework suggests that practice is optimal when the level of challenge is relative to the skill level of the learner (Guadagnoli & Lee, 2004). While studies such as the one conducted by Gray (2017) used a method of adaptive training based on the challenge point framework, that study used a customized VR system that allowed for the virtual environment to be adaptable. Commercially available systems might not provide the level of challenge to be as adaptable to the degree that has been previously used, creating a learning environment that is potentially sub-optimal. Thus, future research can broaden the scope by testing transfer of learning from immersive VR to the RW by investigating people of varying skill levels (Michalski et al., 2019a).

Additionally, the studies summarized in this review have investigated how skills such as golf putting (Harris et al., 2020b), dart throwing (Drew et al., 2020) and table tennis serve returns (Michalski et al., 2019b; Oagez et al., 2022) can be practiced in immersive VR and transferred to the RW. However, skills that require jumping might not benefit from practice in VR. Cochran et al. (2021) found when comparing performance of a single-leg horizontal long jump, participants performed best in the RW. This could be due to the physical nature and weight of the headset causing an interference, resulting in a limitation of body transport (Miles et al., 2013). Although another explanation, based on Gentile's (2000) taxonomy, is that jumping does not require object manipulation but instead requires body transport. Other skills that do not require object manipulation but require body transport should be investigated to understand how the results of studies investigating skills requiring object manipulation (Drew et al., 2020; Harris et al., 2020b; Michalski et al., 2019b; Oagez et al., 2022) can be generalized to skills requiring body manipulation or, body manipulation and object manipulation. Additionally, task complexity may influence how motor skills are learned in VR. In previous motor learning research (Becker & Smith, 2013; Magill & Hall, 1990; Schmidt et al., 1990; Wulf, 2013; Wulf & Shea, 2002), the type of skill has been shown to interact with the learning effect. Thus, it is possible that a similar interaction between the skill type and learning effects in a VR environment can occur as well. For example, within the contextual interference literature, the contextual interference effect, which results in better learning from higher amounts of contextual interference, is influenced by the characteristics of the skill (Wulf & Shea, 2002). Performing a skill with variations that are more dissimilar than similar (i.e., controlled by different rather than the same generalized motor program) result in a greater contextual interference effect, enhancing motor learning (Magill & Hall, 1990). Similarly, skill differences have been shown to interact with motor learning effects within the focus of attention literature. Specifically, Becker and Smith (2013) showed that the learning benefit from an external focus of attention was greater in a complex task compared to a simpler task. Lastly, research investigating augmented feedback has also shown that the type of skill interacts with motor learning effects (for a review see Wulf & Shea, 2002). Schmidt et al. (1990) found that the optimal number of summary trials for more complex tasks was lower relative to more simple tasks. Taken together, previous motor learning literature such as contextual inference, focus of attention, and augmented feedback have shown that type of skill can influence motor learning (Becker & Smith, 2013; Magill & Hall, 1990; Wulf, 2013; Wulf & Shea, 2002). Based on this large body of evidence, it is possible to see a similar learning effect from the interaction of skill type within VR.

Additionally, the level of fidelity and immersion have both been proposed to play a role in the transferability of motor skills (Drew et al., 2020; Harris et al., 2020a; Harris et al., 2020b; Harris et al., 2021). Studies have shown differences in performance due to fidelity between a virtual and real environment (Bufton et al., 2014; Covaci et al., 2015; Magdalon et al., 2011; Vine et al., 2014). Likewise, the level of immersion has been shown to impact cognitive load (Frederiksen et al., 2020), but little is known about the impact fidelity and immersion have on transfer of learning. Harris et al. (2020b) and Harris et al. (2021) suggested that fidelity might be even more important than immersion when considering effective transfer. Given that research has shown that simply achieving the highest level of fidelity does not appear to yield the best outcome, the effects of fidelity are likely more nuanced (Gray, 2019). Specifically, physical, psychological, affective, and biomechanical fidelity are likely to play an important role in a positive transfer of learning (Harris et al., 2020a). Given the theoretical basis of transfer of learning, suggesting similarities between the characteristics of a skill, the environment in which the skill is performed (Thorndike, 1914), and the cognitive processes that occur during the performance of the skill and environment (Lee, 1988), it is hypothesized that the physical, psychological, affective, and biomechanical fidelity impact the degree of which a skill performed in VR positively transfers to a RW (i.e., non-VR) environment. Thus, future investigation is required to fully understand the impact of both immersion and fidelity for the transfer of leaning in immersive VR.

It has also been proposed that VR might provide an advantage given the level of motivation and engagement it provides a user compared to a traditional learning environment (Gray, 2019; Lohse et al., 2016). It's important to note that in the context of the present review, motivation is operationally defined as a psychological property that encourages action toward a goal that increases and/or sustains goal directed behavior. Engagement is defined as the affective quality or experience of a person and properties such as reward, choice, and interactivity are all thought to impact one's level of engagement (Lohse et al., 2016). Therefore, engaging environments are predicted to be motivating, but motivation does not guarantee engagement. It's possible that motivation and engagement impact VR learning both indirectly and directly. First, an increased level of motivation and engagement have been proposed to *indirectly* influence skill learning due to the potential increase in the amount of practice a learner chooses to perform (O'brien & Toms, 2008). However, there is some neurophysiological evidence in rodents that suggests motivation and engagement have *direct* effects on learning. Specifically, studies have found that enriched environments can increase the number of synapses per neuron (Anderson et al., 1994) and increase the retention of new neurons (Kempermann et al., 1997) compared to non-enriched, control environments. More recently, however, Lohse et al. (2016) showed that increased engagement in humans via a virtual gaming environment not only can have indirect effects on learning, but also direct effects compared to a sterile environment. Specifically, this study showed that performance curves were similar during the acquisition phase, but significantly different during the retention test. Thus, Lohse et al. (2016) proposed that the psychological processes that occurred during acquisition due to an increased engagement may alter the memory consolidated process. Taken together, these studies suggest that motivation and engagement may facilitate learning improvements through the use of VR. Future research should examine how motivation and engagement are influenced as a result of VR motor skill practice. Such future investigations could determine whether VR practice, compared to traditional, RW environments, enhances the learning process both directly and indirectly as other experiments have shown within enriched (Anderson et al., 1994; Kempermann et al., 1997) and gaming environments (Lohse et al., 2016). Specifically, it is beneficial to know whether the proposed notion that VR enhances motivation and engagement during practice, as compared to RW practice, leads to individuals engaging in a greater amount of practice and/or whether there is a direct learning benefit. Such findings would suggest that VR could be an effective alternative to traditional, RW motor skill practice.

Lastly, another important consideration stems from the experiments conducted to test the practice specificity hypothesis. The findings from this research led to two important conclusions. First, if the type and the amount of sensory information available during the acquisition phase of a motor skill is changed, the performance during the transfer test should be negatively affected. Second, this negative effect is increased with the amount of practice performed during the acquisition phase (Proteau, 1992). While VR attempts to replicate the information available during a physical environment, it is possible that information differences exist between the virtual and physical environment (e.g., visual, haptic, auditory, etc.). Evidence of these differences have been observed when comparing the kinematics between the virtual and physical groups during the acquisition phase of a task (Drew et al., 2020). Additional evidence that informational differences exist is the fact that transfer appears to be one directional (Harris et al., 2020b; experiment two). That is, practice in VR has led to increased RW performance but RW practice has not led to improved VR performance. If these differences exist, a negative effect on performance might not be observed until a learner has performed an extended amount of practice within the VR environment as the learner becomes more "specified" to that environment. Based on the predictions of the practice specificity hypothesis, it is hypothesized that a negative effect on learning would be observed as the amount of practice increases if these sensory information differences existed between the two environments (Adam et al., 1972; Proteau, 1992; Proteau & Marteniuk, 1991). Manipulating the number of trials performed during VR practice would allow this prediction to be tested. Specifically, by comparing VR and RW motor skill practice, increasing the number of trials performed during practice, and assessing learning in the RW at multiple time points, would allow the researcher to determine whether learning continues to improve at a similar rate in VR compared to RW practice.

In sum, VR technology provides a promising future, yet much remains unknown and further investigations are required to understand the extent to which VR practice enhances RW performance. Given the mixed findings reviewed above, it should not be assumed that practicing a motor skill in VR leads to a performance improvement within a physical environment. To further understand the generalizability of immersive VR practice, future research should examine the amount of time between VR practice and the RW performance assessment. Additionally, studies should investigate how skill level and skill type influence transfer of learning as well as the impact of type of immersion and level of fidelity. Lastly, researchers should investigate the psychological aspects of VR practice as well as manipulate practice duration to understand if transfer of learning changes with greater amounts of practice.

This purpose of this dissertation will be to examine intrinsic motivation and neural activity, in relation to VR motor learning, and the effects of practice duration on transfer of learning following motor skill practice in VR. Specifically, this dissertation will consist of two experiments. Experiment one investigated the psychological aspects and transfer of learning from the practice of a motor skill in VR. Experiment one also investigated how intrinsic motivation and engagement compared between VR and RW practice. Additionally, this study examined differences in RW performance using a golf putting task following VR or RW practice. The purpose of experiment two will be threefold: 1) to investigate the transfer of learning effects following multiple days of VR golf putting practice and whether extended amounts of practice lead to lower levels of learning compared to RW practice, 2) to investigate the differences in neural activity, as measured via EEG, between virtual and RW practice, and 3) to examine intrinsic motivation following an extended amount of VR practice.

Chapter I: Experiment One: The Psychological and Transfer of Learning Effects from Immersive Virtual Reality Motor Skill Practice

Abstract

While research has shown improvements in real-world performance from practice within an immersive virtual reality (VR) environment, other studies have revealed contradicting results. However, given that VR is frequently used for its learning benefits, further research is warranted. Increased motivation is one possible advantage VR might provide compared to a real environment. Similarly, a recent study has shown an enriched gaming environment led to higher levels of engagement that resulted in a direct learning benefit. Therefore, the purpose of this study was to compare the intrinsic motivation, engagement, and transfer of learning differences between VR practice and real-world practice of the same motor skill. This experiment tested the hypothesis that measures of intrinsic motivation and engagement would be greater when practicing a task in VR compared to physical practice. Furthermore, it was predicted that VR practice would result in similar performance improvements. Participants (n = 61) were randomly assigned to a physical, real-world (RW) practice group (n = 30) and a VR practice group (n = 31) in which they performed a miniature golf putting task. On day one, participants completed an intrinsic motivation inventory (IMI), performed a 10-trial pre-test, a 50-putt acquisition phase, an O’Brien engagement scale, and completed a second IMI following the acquisition phase. On day 2, participants returned to perform a 10-trial post-test. A 2 (condition) x 2 (test phase) repeated measures ANOVA revealed a significant change in intrinsic motivation scores (p = .003). Post hoc analysis showed that VR practice led to a significantly greater increase in the average IMI score compared to RW practice. No differences were found for engagement. Analyses for performance showed that there was a statistically significant ($p < .001$) improvement in accuracy

(i.e., radial error), but the two groups did not differ from one another. An additional analysis for performance showed that there were no significant changes in precision (i.e., bivariate variable error). Overall, these results are in partial support of the hypotheses and suggest that VR practice of a motor skill led to a significantly greater increase in motivation compared to RW practice. Additionally, these results suggest that VR practice was similarly effective compared to RW practice. Directions for future research are discussed.

Introduction

Developing a level of mastery for a motor skill requires a significant amount of quality practice (Ericsson et al., 1993). However, depending on the skill, numerous barriers exist that make it difficult to attain an adequate amount of practice. For example, many sports require a field or gymnasium, as well as at least one if not multiple individuals to assist in practice. Pilots require access to a plane, helicopters, or a simulator to gain experience, which comes at the cost of personal injury or financial expenses. The use of virtual reality (VR) has been considered a method for overcoming such logistical, inconvenient, and costly obstacles (Michalski et al., 2019). Additionally, it allows for the utilization and implementation of optimal learning principles that have been rigorously tested for numerous decades (Weiss et al., 2014; Wulf, 2007). Previous research has demonstrated practice in VR can outperform traditional practice when the VR practice difficulty is adapted based on the skill level of the individual (Gray, 2017). While VR should not be recommended as a replacement for traditional practice, it does potentially offer numerous advantages.

First, though the research is still in its infancy, there is empirical evidence supporting the conclusion that practicing a motor skill in VR can be effective for improving real-world (RW) performance (Harris et al., 2020; Michalski et al., 2019; Oagaz et al., 2021). This evidence exists for both immersive (e.g., head mount display) and non-immersive (e.g., CAVE system) VR (Gray, 2017; Oagaz et al., 2021). However, the immersive VR evidence is scarce and not all the experiments that have tested transfer of learning from an immersive virtual environment to a RW environment have provided evidence to support this conclusion (Drew et al., 2020; Harris et al., 2020, experiment 1). For example, Drew et al. (2020) showed that immersive VR practice resulted in decreased performance compared to the pretest. Thus, given the minimal amount of research that has examined transfer of learning in immersive VR, more research is warranted to understand what does and does not result in RW performance improvements.

The transfer appropriate processing theory (Lee, 1988) and the identical elements theory (Thorndike, 1914), later developed into identical production model (Singley & Anderson, 1989), have been proposed to explain transfer of learning. These theories purport that similarities must exist between the practice environment and the performance environment to achieve positive transfer of learning. More specifically, the transfer appropriate processing theory predicts that positive transfer is a result of cognitive processing similarities between the practice and testing environments (Lee, 1988). In comparison, the identical elements theory suggests that transfer is due to the similarities between movement characteristics executed during practice and testing environments (Thorndike, 1914). Based on research that has tested these theories, it is likely that both, at least to a degree, contribute to a positive transfer of learning effect (Lee, 1988; Singley & Anderson, 1989). Therefore, it can be anticipated that the extent to which positive transfer occurs is influenced by the skill characteristics, environmental context, and the cognitive processes that are shared between the practice and testing environments. Such explanations also align with practice specificity research indicating that the sources of information available within the testing phase should be similar to the information available during the practice phase (Proteau, 1992; Proteau et al., 1992). Thus, if VR provides task, environment, and cognitive similarities to those within the physical environment, it would be predicted that VR motor skill practice would facilitate RW performance improvements and transfer of learning.

In addition to the possible RW performance improvements following VR practice, VR has been proposed to potentially enhance motivation and engagement compared to traditional practice (Gray, 2019; Lohse et al., 2016). As suggested by Wulf & Lewthwaite (2016), psychological properties, such as motivation, are factors that likely contribute to motor performance and learning. Both extrinsic and intrinsic motivation have been shown to have learning benefits (Abe et al., 2011; Gruber et al., 2014). Such benefits have been proposed to be indirect through increased amount of practice (O'Brien & Toms, 2008), and direct via neurophysiological evidence (Anderson et al., 1994; Kempermann et al., 1997). For both types of motivation, neuroimaging studies suggest that this learning benefit is influenced by the dopaminergic pathways and hippocampus during practice (Adcok et al., 2006; Gruber et al., 2014). Additionally, research in rodents have shown that enriched environments can increase the number of neuron synapses (Anderson et al., 1994) and neuron retention (Kempermann et al., 1997) when compared to a sterile environment. More recently, work by Lohse et al. (2016) found support for a direct influence on learning in humans. This study showed that a task performed in an enriched gaming environment led to increased engagement and learning compared to the same task performed in a sterile environment (Lohse et al., 2016). Thus, a motor skill practiced in VR could elicit similar motivational and engagement improvements compared to an enriched environment, and lead to possible indirect and direct learning benefits.

To our knowledge, no study has directly assessed whether a motor task performed in immersive VR influences intrinsic motivation or engagement during practice. Thus, the purposes of this study were: 1) to replicate previous studies that have tested the transfer of learning effects following immersive VR motor skill practice and 2) to compare intrinsic motivation and engagement between motor skill practice in an immersive virtual and real environment. Based on previous research examining VR transfer of motor learning (Michalski et al., 2019; Porter & Cochran, 2019), it was predicted that VR practice would result in performance improvements. Specifically, it was hypothesized that the RW posttest would reveal a significant decrease in radial error (RE) and bivariate variable error (BVE) when compared to the pretest. Moreover, it was predicted that no significant group differences would be found for RE or BVE. Furthermore, it was predicted that the VR posttest would not reveal significant group differences. Additionally, it was predicted that VR practice would lead to greater intrinsic motivation and engagement following practice compared to RW practice.

Method

Participants

A total of 64 university students (males = 21; females = 43) between the ages of 18-30 years old (*M* = 21.97, *SD* = 2.45) volunteered to participate in the present experiment. A total of 61 participants completed the study. Participants were informed they would practice a golf putting task and that they would use VR but were naïve to the purpose of the study. The mini simulator sickness questionnaire (MSSQ) was used to determine participants susceptibility for motion sickness. Participants who scored 26 or higher were excluded from the study. The university's institutional review board approved the study, and the students completed an informed consent form prior to participation.

Task and Apparatus

The data collected for this experiment took place in a climate-controlled research laboratory. The RW golf putting task was performed on an artificial grass carpeted surface (1.829 x 3.658 m) inside the laboratory. Participants used a standard length (90 cm) golf putter to putt a regulation sized golf ball towards a target which was the size of a standard cup hole (diameter 10.795 cm). The hole was 2.438 meters away from the starting line. A web camera was fixed perpendicularly above the target to capture the golf ball position relative to the center of the target. The camera application (Microsoft Corporation; version 2021.105.10.0) on an Alienware computer was used for video capture. Tracker software (version 6.0.1) was used to determine the x and y coordinates of the at rest golf ball.

The Oculus Quest 2 VR headset and Cloudlands VR Minigolf application were used to create a virtual miniature golf putting course that was designed to replicate the course in the physical environment. The same shape and dimensions of the RW putting surface were replicated in the VR environment. Participants used a virtual golf putter to putt a virtual ball into a virtual hole while wearing the Oculus Quest 2 and holding one Oculus controller in their dominate hand. The researcher recorded the golf ball's Euclidian distance from the hole, which was provided from the Cloudlands VR Minigolf application.

Procedure

Participants were randomly assigned into one of two groups: VR practice (n = 31) and RW practice (n = 30). After signing the consent form, the participants completed an intrinsic motivation inventory (IMI) and the O'Brien engagement scale in a counterbalanced order. After the participants completed the questionnaires, the researcher provided instructions followed by a demonstration of the golf putting task. Participants were instructed to hit the ball to the center of the target or as close to the center of the target as possible.

The experiment took place over two consecutive days with the questionnaires, pretest, practice phase, and the same two questionnaires occurring on day one in that order. The posttest occurred on day two (see figure 3). The pre- and post-test phases were identical for both groups. During the pre- and post-testing phases, participants putted a golf ball 10 times on the carpeted surface towards the center of the target. The practice phase consisted of 50 total putts within the

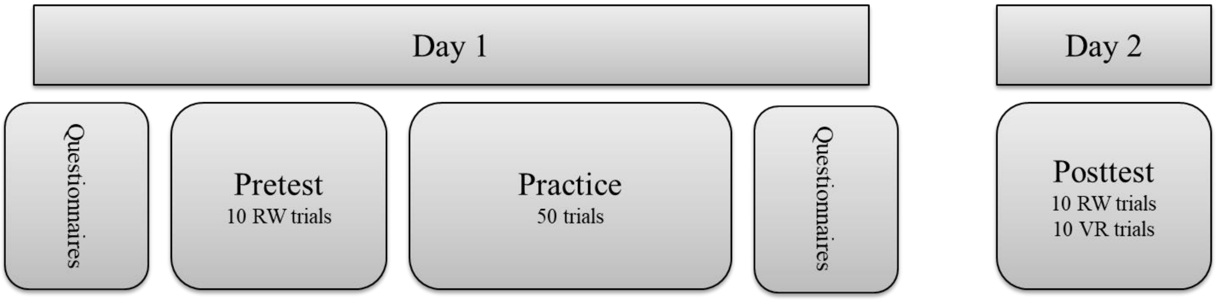

Figure 3. Schematic representation of the experimental design.

respective environment (VR; RW). Participants returned within 48 hours to complete the posttests. The posttests included 10 trials in the physical environment and 10 trials in the virtual environment.

Putting performance data were collected to determine the accuracy (i.e., radial error) and precision (i.e., bivariate variable error). The putting target was considered the origin of a two-dimensional grid with the coordinates 0,0. Radial error (RE), a two-dimensional equivalent of absolute error was calculated for each trial using the Pythagorean theorem to calculate the Euclidian distance of the two closest points between the golf ball and the center of the target.

$$RE = (x^2 + y^2)\ \frac{1}{2}$$

Bivariate variable error (BVE), the two-dimensional equivalent of variable error, was calculated by taking the square root of the squared mean distance of each trial from the centroid (*c*) of each block of *k* trials.

$$BVE = \left(\frac{1}{k}\sum_{i=1}^{k}(x_i - x_c)^2 + (y_i - y_c)^2\right)^{\frac{1}{2}}$$

Data Analysis

Data were analyzed using IBM SPSS Statistics version 28.0.0. There were seven separate 2 (group) x 2 (test) repeated measures analysis of variance (ANOVAs) used to assess the average intrinsic motivation scores and four subscales (interest/enjoyment, perceived competence, effort/importance, value/usefulness), accuracy (radial error), and consistency (bivariate variable error). An independent samples t-test was used to determine RE group differences in the VR posttest. An independent samples t-test was used to determine engagement score differences between groups.

Results

Performance Variables

Accuracy (Radial Error). A 2 (group) x 2 (test) repeated measures ANOVA was used to determine accuracy differences between groups and tests. The analysis revealed a main effect for test, $F(1, 60) = 15.674$, $p < .001$, $\eta_p^2 = .207$. Pairwise comparisons for test indicated that both groups significantly decreased radial error from pretest to posttest, $p < .001$. No significant differences were observed for the test x group, $p = .132$, or between-subject effects tests, $p = .738$ (see figure 4).

Precision (Bivariate Variable Error). A 2 (group) x 2 (test) repeated measures ANOVA was used to determine consistency differences between tests and groups. There was no significant main effect for the test $F(1, 60) = 2.536$, $p = .117$, $\eta_p^2 = .041$, the test x group interaction $F(1, 60) = .025$, $p = .874$, $\eta_p^2 = .000$, or the between-subject effects tests $F(1, 60) = 1.579$, $p = .214$, $\eta_p^2 = .026$.

Psychological Variables

Average Intrinsic Motivation. A 2 (group) x 2 (test) repeated measures ANOVA was used to determine average intrinsic motivation score differences between groups and tests. The analysis revealed a significant main effect for test $F(1, 59) = 37.827$, $p < .001$, $\eta_p^2 = .391$. The analysis also revealed a significant test x group interaction, $F(1, 59) = 8.379$, $p = .005$, $\eta_p^2 = .124$. Furthermore, the test of between-subject effects revealed a non-significant effect, $p = .173$.

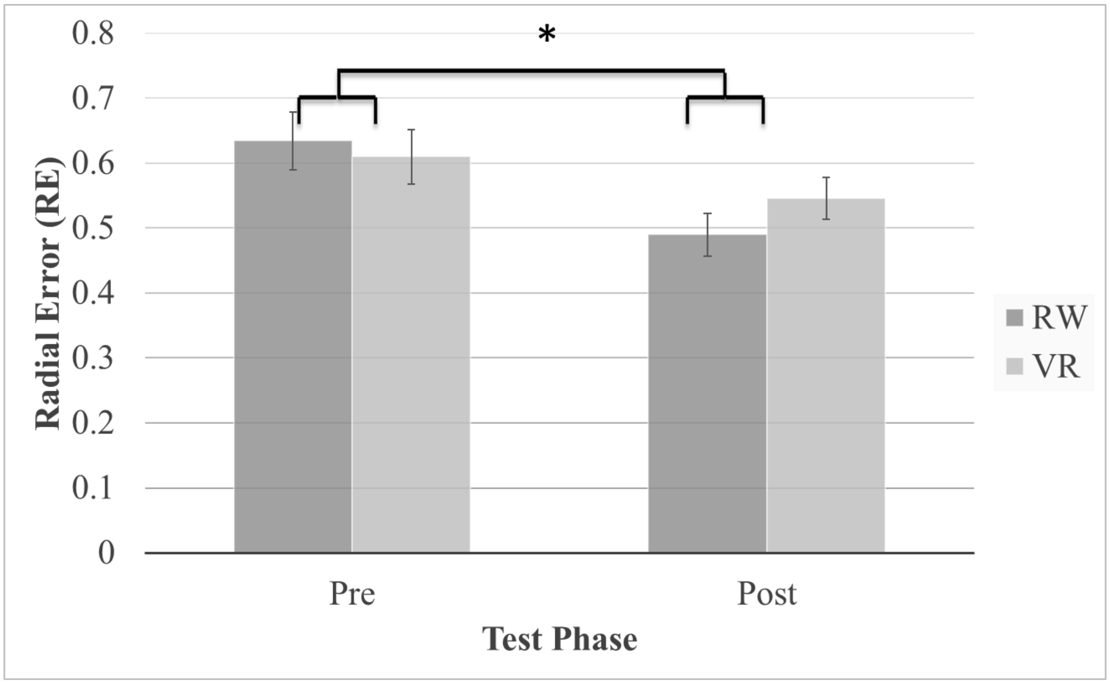

Figure 4. Mean radial error (RE) for pre- and post-tests for virtual reality (VR) and real-world (RW) practice groups. The * indicates significant differences between groups. Error bars represent standard error (SE).

Considering the significant interaction, pairwise comparisons were made (see figure 5). Pairwise comparisons revealed non-significant differences between VR (*M* = 4.46, *SD* = 0.76) and RW (*M* = 4.36, *SD* = 0.83) at pretest, *p* = .635, but showed that the VR scores (*M* = 5.05, *SD* = 0.86) were significantly higher during the posttest compared to RW scores (*M* = 4.57, *SD* = 0.94), *p* = .045. Additional pairwise comparisons showed that both the VR, *p* < .001, and RW, *p* = .026, scores significantly increased from pre- to post-test.

Interest/Enjoyment. A 2 (group) x 2 (test) repeated measures ANOVA was used to determine interest/enjoyment score differences between groups and tests. The analysis showed a significant main effect for test *F*(1, 59) = 54.394, *p* < .001, η_p^2 = .480. The analysis also found a significant test x group interaction *F*(1, 59) = 11.795, *p* = .001, η_p^2 = .167. The test of between-subjects' effects was non-significant, *p* = .213. Pairwise comparisons showed that the VR (*M* = 4.50, *SD* = .188) and RW (*M* = 4.50, *SD* = .191) scores were not significantly different, *p* = .993. However, the comparison revealed the posttest VR score (*M* = 5.521, *SD* = .195) was significantly higher compared to the RW score (*M* = 4.87 *SD* = .199). Additional pairwise comparisons showed that both the RW, *p* = .008, and VR, *p < .001*, groups significantly increased scores from pre- to post-test (see figure 5).

Perceived Competence. Following a 2 (group) x 2 (test) repeated measures ANOVA, results revealed a significant main effect for test *F*(1, 59) = 10.799, *p* = .002, η_p^2 = .155. The competence scores for both groups significantly increased from pre- to post-test. No significant interaction, *p* = .147, or between-subjects effects, *p* = .447, were found.

Effort/Importance. To test for group and test differences for effort/importance scores, a 2 (group) x 2 (test) repeated measures ANOVA was used. No significant main effects were found for test, *p* = .254, or between groups, *p* = .765.

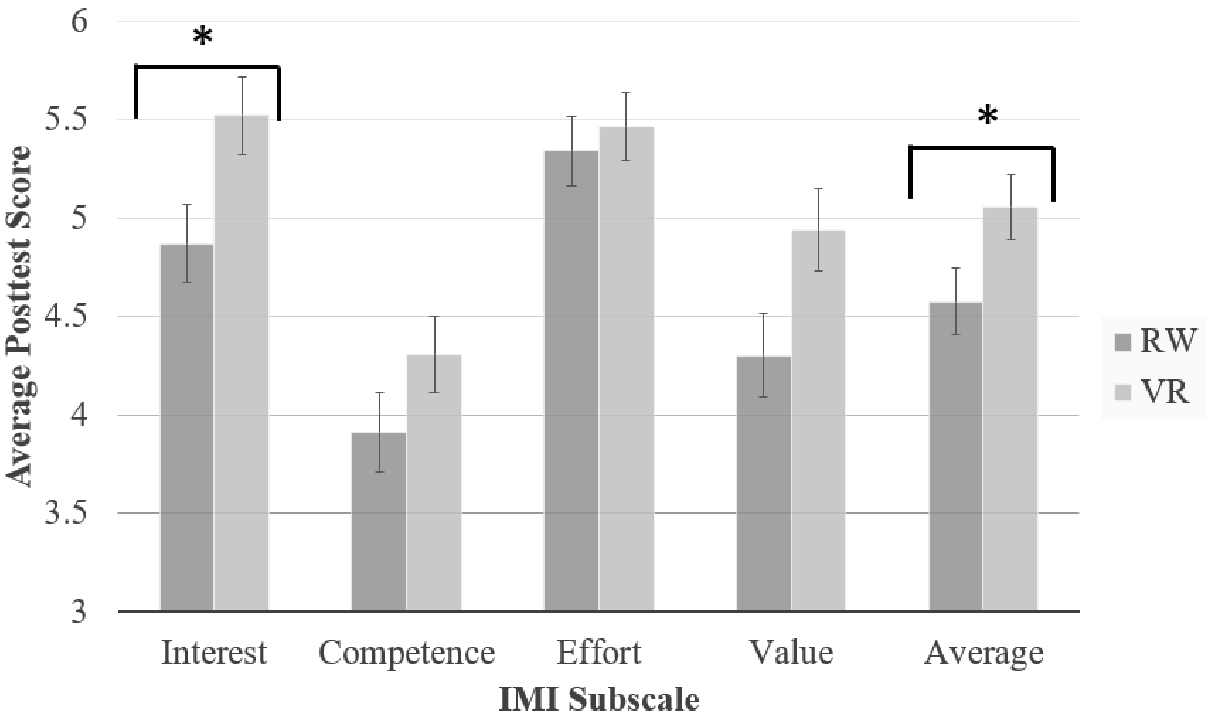

Figure 5. Intrinsic Motivation Inventory Score Differences. The * indicates significant differences between groups. Error bars represent standard error (SE).

Value/Usefulness. A 2 (group) x 2 (test) repeated measures ANOVA was used to determine value/interest score differences between groups and tests. The analysis revealed a significant main effect for test $F(1, 59) = 24.452$, $p < .001$, $\eta_p^2 = .293$. The test x group interaction did not reveal a significant main effect, $p = .105$. Similarly, the between-subjects main effect did not yield a significant effect, $p = .056$. Pairwise comparisons for test showed both groups significantly increased scores from pre- to post-test.

Engagement. An independent samples t-test was used to compare posttest engagement scores between groups. The t-test revealed that engagement scores for the VR group ($M = 4.35$, $SD = .668$) were significantly different to the RW group ($M = 4.362$, $SD = .467$), $t(58) = .032$, $p = .487$.

Discussion

The present study examined the effects of immersive VR practice on transfer of learning during a golf putting task. Additionally, this study investigated the effects of VR practice on intrinsic motivation and engagement. It was predicted that VR practice would facilitate a positive transfer of learning to a RW environment, and the performance improvements would be similar for both virtual and RW groups. It was also hypothesized that VR practice would lead to higher levels of intrinsic motivation and engagement compared to RW practice. The results partially supported our hypotheses.

Performance Variables

First, the results from the RE analysis support the hypothesis. Specifically, the analysis showed that the RE in both groups significantly decreased from pretest to posttest and no differences were observed between groups. These results suggest that immersive VR practice led to a positive transfer of learning and resulted in a motor learning effect that was relatively similar compared to RW practice. Particularly, both types of practice resulted in improvements in accuracy. These findings are congruent with previous research supporting the finding that VR results in RW motor performance (Harris et al., 2020, experiment 2; Michalski et al., 2019; Oagaz et al., 2021). For example, Michalski et al. (2019) found that VR practice led to significant performance improvements in table tennis strokes and led to a higher performance compared to a no practice control group. Similarly, the second experiment of Harris et al. (2020) showed that both RW and VR practice of a golf putting task led to increased RW accuracy and no differences were found between practice conditions. However, two experiments that have recently investigated this topic contradict the findings from the current study and demonstrated that VR practice led to a decrease in RW motor performance (Drew et al., 2020; Harris et al., 2020, experiment 1). Unlike the present study, and research that has found evidence for a positive transfer of learning (Michalski et al., 2019; Oagaz et al., 2021), the experiments that found performance impairments following VR practice performed a posttest immediately following practice instead of performing it at least one day following acquisition. Thus, it is possible that the amount of time between VR practice and RW posttest could influence transfer of learning.

While other VR studies that have used accuracy tasks typically have not used BVE as a measure of performance (e.g., Harris et al., 2020; Michalski et al., 2019), motor learning research has commonly used BVE to assess precision of an accuracy task (e.g., Frank et al., 2015; Hancock et al., 1995). Additionally, BVE has been suggested to be an essential measure of motor learning (Schmidt et al., 2018). The results from the analysis of the BVE data in the current study did not support the experimental hypothesis. Contrary to the hypothesis, these results suggest that neither group increased golf putting precision due to practice, nor were there differences between groups. Previous research has shown that precision and accuracy can be influenced by practice differently (Edwards et al., 2005; Kumar et al., 2017). Nonetheless, it was predicted to observe improvements in precision for both groups. During the acquisition phase of this experiment, the amount of variability between each putting trial was minimal. That is, participants putted all 50 trials from the same location. A large amount of motor learning research has shown a significant motor learning advantage when variability between trials is introduced (Schmidt et al., 2018; Shea & Kohl, 1990, 1991). Thus, it is possible that the lack of variability between practice trials negated the practice effect of precision. Future research comparing transfer of learning between VR and RW practice should use a practice schedule that induces practice variability.

Psychological Variables

Regarding the psychological measurements, the experimental hypotheses were partially supported. The results from the intrinsic motivation measurements support the current study’s predictions. Specifically, it was shown that VR and RW practice significantly increased participants’ average intrinsic motivation. However, VR led to a greater increase compared to RW practice, as evidenced by the significantly higher scores during the posttest. When examined by the subscales, both VR and RW practice significantly increased interest and enjoyment, however, practice in VR led to a greater increase. The results for perceived competence and effort and importance showed that both VR and RW groups increased scores, whereas there was no change in value and usefulness observed for either group.

The results of the present study confirm the prediction made by Gray (2017), suggesting that practicing a motor task in VR could offer a learning environment that is more motivating compared to RW practice. Such a finding can be valuable given that increasing intrinsic motivation has been shown to facilitate motor performance (Wulf & Lewthwaite, 2016) and previous work has demonstrated indirect (Hunicke et al., 2004) and direct (Abe et al., 2011; Gruber et al., 2014) learning benefits. It is worth noting the increase in intrinsic motivation occurred after only one session of practice. Thus, whether this motivational increase in VR remains elevated after multiple practice sessions in VR is unknown. Interestingly, previous research that has investigated novelty of learning environments has shown when individuals are exposed to a new learning context, perceived novelty increases and is associated with an increase in intrinsic motivation (Jeno et al., 2019). Specifically, the appraisal of novelty has been shown to predict higher levels of interest (Adachi et al., 2017). However, the increase in novelty and motivation has been shown to decrease with repeated exposure to the learning context (Keller & Suzuki, 2014). Such findings may explain the intrinsic motivation results found in the current study. That is, the increase in intrinsic motivation could be a product of VR being a novel environment. This is further supported in that the only subscale that revealed group differences during the posttest was interest and enjoyment, consistent with findings reported in previous novelty research (Adachi et al., 2017). Therefore, further investigation is warranted to understand if this observed increase in motivation remains elevated after repeated exposure to VR practice.

Contrary to the motivation hypothesis, the prediction made for the engagement scores were not supported by the findings of experiment one. Unlike Lohse et al. (2016), the results of this study revealed no significant differences between the VR and RW groups during the posttest. The experiment by Lohse et al. (2016) compared a computer task performed within a sterile environment to the same task in a gamified environment. In the present study, the environments were different, but it is possible the environments were not different enough to result in self-reported engagement differences. For example, the VR environment in the present study was not gamified, unlike the environment utilized by Lohse et al. (2016). Therefore, it is possible that this lack of gamification contributed to the lack of observed differences. It is also worth noting that the engagement analysis was statistically underpowered. Thus, future research is warranted to understand whether there are engagement differences between VR and RW practice.

Experiment One Conclusion

The present study shows that VR practice results in similar RW performance improvements and higher interest compared to RW practice. These results are promising for VR technology as few studies have sought to investigate the transferability of VR practice of a motor skill to a RW environment. This study is one of the few that provides evidence for a positive transfer of learning effect and replicates previous findings (Harris et al., 2020, experiment 2; Michalski et al., 2019; Oagaz et al., 2021). Moreover, this is the first study to compare intrinsic motivation and engagement differences during the practice of a motor skill between VR and RW environments. However, it is worth noting that the amount of practice performed is a primary limitation. The practice specificity hypothesis purports two primary claims. That is: 1) if information differences exist between the acquisition and testing phase there will likely be a decrease in performance during the testing phase and 2) this negative performance effect will increase as the amount of practice is increased (Proteau, 1992). Thus, given that information differences likely exist between a VR and RW environment, it is predicted that an extended amount of VR practice would lead to transfer of learning differences compared to RW practice. Such performance differences should be observed between VR and RW practice during a RW posttest. Additionally, the increase in intrinsic motivation may simply be a result of novelty during VR practice (Jeno et al., 2019). If such an observation is due to novelty, increasing the amount of practice might lead to a decrease in novelty and thereby decrease motivation (Adachi et al., 2017). Thus, increasing the amount of practice and measuring performance and intrinsic motivation across multiple time points is one way to overcome such methodological limitations.

Chapter II: Experiment Two: Investigating the Transfer of Learning, Psychological, and Neural Effects from Extended Practice in Immersive Virtual Reality

Abstract

Previous studies have provided empirical evidence that practice in an immersive virtual reality (VR) environment results in similar performance improvements compared to physical practice in a real-world (RW) environment. A current limitation within the VR literature is the comparison of motor performance and learning improvements between VR and RW environments as a product of an extended period of practice. Studies testing the practice specificity hypothesis suggest that if information discrepancies exist between two environments, transfer of learning effects may only become apparent following moderate to large amounts of practice. The purpose of this experiment was to practice a motor skill across several days in VR and RW environments to compare the transfer of learning, intrinsic motivation, and neural activity differences. Participants (n = 42) were randomly assigned to a VR (n = 22) or a RW (n = 20) practice condition. On days 1-3, participants performed a 10-trial golf putt pre-test followed by a 60-golf putt practice phase while wearing an EEG headset. A 10-trial post-test was conducted on day 4. Analyses revealed that both groups significantly reduced radial error (i.e., accuracy), $p < .001$, $\eta_p^2 = .303$, and bivariate variable error (i.e., precision), $p < .001$, $\eta_p^2 = .232$. However, there were no between group performance, intrinsic motivation, or neural activation differences. These findings partially support the predictions made and are consistent with previous work. In sum, this study suggests that practicing motor skills in VR and RW results in similarities in motor performance improvements, learning effects, and brain activity readings.

Introduction

Virtual reality (VR) has recently become a popular method for practicing motor skills in a variety of fields. Specifically, immersive VR is currently used in sport, military, and rehabilitation, in addition to other domains (Gray, 2017; Levin et al., 2015; Pallacivini et al., 2016). Apart from individuals, teams, and companies adopting VR due to the appeal of using the latest technology, several benefits have been proposed within the scientific literature. Depending on the motor skill, developing mastery can require practice that is logistically complicated, personally risky, and financially costly (Michalski et al., 2019). VR provides an opportunity to overcome such barriers. Moreover, VR affords the possibility to create software that aligns with decades of research that have been dedicated to understanding the practice design for optimal learning and performance (Weiss et al., 2014; Wulf, 2007). Furthermore, VR has been proposed to be psychologically beneficial. Specifically, Gray (2019) suggested that practicing a motor skill in VR might be more motivating compared to traditional learning environments and experiment one of the present dissertation (Markwell et al., in press) provided empirical evidence to support this notion. In addition to this recent research, studies have also found evidence that motor skill practice in VR can facilitate a positive performance improvement in a real-world (RW) environment (Harris et al., 2020; Markwell et al., in press; Michalski et al., 2019; Oagaz et al., 2021). Such findings can be explained by previous transfer of learning theories. The transfer appropriate processing theory (Lee, 1988) and identical elements theory (Thorndike, 1917) propose that the more cognitive processing and movement characteristic similarities that exist between two separate environments, the greater the amount of learning that will be transferred from one environment to the other.

In experiment one (Markwell et al., in press), we investigated performance and psychological differences following the practice of a motor task in a VR or RW environment. Participants practiced a golf putting task for 50 trials in their respective group (VR or RW). The analysis revealed that both groups significantly improved their golf putting accuracy and no significant differences were found between groups, indicating that VR practice resulted in similar RW performance improvements relative to traditional practice. Additionally, the analysis revealed VR practice led to a greater increase in intrinsic motivation, evidenced by the interest/enjoyment subscale score on the Intrinsic Motivation Inventory (IMI) during posttest compared to the RW practice group. The interest/enjoyment subscale has been shown to be the measure of intrinsic motivation (Center for Self-Determination Theory, 2023; Ryan & Deci, 2004). Interestingly, of the four other IMI subscales which were measured (interest/enjoyment; perceived competence; effort/importance; value/usefulness), the interest and enjoyment subscale was the only one that resulted in a significant difference compared to RW practice during the posttest. Such findings could be a result of participants perceiving VR practice as a novel environment. Previous research found that perceived novelty increased when individuals were exposed to a new learning context (Jeno et al., 2019). Additionally, this increase in novelty has been linked to an increase in intrinsic motivation (Jeno et al., 2019) and specifically higher levels of interest (Adachi et al., 2017). However, novelty and intrinsic motivation have been found to decrease due to repeated exposure to the same learning context (Keller & Suzuki, 2014). Therefore, given that there was only one day of practice in experiment one (Markwell et al., in press), the increased intrinsic motivation may have simply been a result of an increased level of interest influenced by the novelty of the VR practice environment. It would then be predicted that repeated amounts of practice in VR would reduce the perceived novelty and the level of interest, ultimately decreasing intrinsic motivation over time.

Another factor to consider is the extent to which learning transfers following repeated amounts of practice. These considerations arise from the experiments conducted to test the practice specificity hypothesis (Adam et al., 1972; Proteau, 1992; Proteau et al., 1992; Proteau & Martenuik, 1991), which led to two primary conclusions. First, if the amount and type of information available during the acquisition period of a motor skill is altered, the performance during the transfer test will be negatively affected. Second, this negative effect is increased as the duration of the acquisition phase is extended (Proteau, 1992). This second conclusion of increased specificity has been thought to be a result of a developed dependency on the information available during the acquisition phase. For example, Adams et al. (1972) conducted an experiment in which participants practiced a linear positioning task for either 15 or 150 trials. The participants performed the task without receiving visual, auditory, or kinesthetic information and then participated in a transfer test in which this afferent information was now available. There was a 13.7 mm increase in error for the participants in the 15-trial group while the participants in the 150-trial group had a 23.6 mm increase in error. These results demonstrate there was an increased specificity with the available information sources as the amount of practice increased. These findings have since been replicated in multiple studies and show similar results indicating that individuals who practiced more had worse performance during a transfer test compared to those who practiced less if the available information was not matched when transferring from practice to post-test (e.g., Adams et al., 1977; Proteau & Martenuik, 1991). Thus, while VR applications used to practice a motor skill can simulate a RW task, differences still exist in the available information (e.g., visual, auditory, haptic, etc.) between the

VR and RW environments (Mishra et al., 2021). Currently, the experiments that have compared RW and VR practice have not examined performance during the posttest at different time points following increasing amounts of practice. Based on the practice specificity hypothesis, such information differences that exist between the VR and RW environments may not reveal posttest performance differences between VR and RW practice groups with modest amounts of practice. However, after moderate to extended amounts of practice, group differences at posttest may be evident.

To understand what similarities or differences may exist between a VR and RW environment, neural activity is one mechanism that can be examined during the acquisition phase of a motor skill (Kober et al., 2021; Wang et al., 2020). Such types of investigation could fall in line with the transfer appropriate processing theory and practice specificity hypothesis, suggesting that the more neural activity differences that exist between a VR and RW motor task, the less that practice in a VR environment will transfer to a RW environment (Proteau, 1992; Lee, 1988). Electroencephalography (EEG) is one method used to assess neural processes by measuring cortical electrical activity. Previous studies have used EEG to determine neural activity differences between VR and RW motor tasks (Baumeister et al., 2010; Kober et al., 2021; Pacheco et al., 2017; Wang et al., 2020). The investigations (Baumeister et al., 2010; Kober et al., 2021; Pacheco et al., 2017; Wang et al., 2020) have compared the cortical activity during the performance of a motor task in a RW environment to both non-immersive and immersive VR. Interestingly, the studies that have shown neural differences between tasks were performed in non-immersive VR and RW environments (Baumeister et al., 2010; Pacheco et al., 2017). This was evidenced by higher theta in the frontal and occipital region, higher alpha in the frontal, parietal, and temporal regions, and higher beta power over the frontal and occipital regions (Baumeister et al., 2010: Pacheco et al., 2017). Ultimately, these results suggest neural process differences between the VR and RW environment (Baumeister et al., 2010: Pacheco et al., 2017). However, more recent work investigating immersive VR showed no neural differences during the performance of motor tasks performed in immersive VR and the RW environment (Kober et al., 2021; Wang et al., 2020).

Taken together, neural activity comparisons between immersive VR and RW environments showed no differences (Kober et al., 2021; Wang et al., 2020), whereas comparisons between non-immersive VR and RW environment showed differences (Baumeister et al., 2010: Pacheco et al., 2017). These incongruent results could be due to immersive VR systems providing a higher level of immersion, thus minimizing the neural process differences between VR and RW environments (Kober et al., 2021). However, both studies that investigated differences in immersive VR compared to a RW environment used simple reaching tasks which required the control of only a few degrees of freedom (Kober et al., 2021; Wang et al., 2020). Whereas the studies investigating the neural activity differences within non-immersive VR used more complex tasks such as golf putting (Baumeister et al., 2010) and a full body step up task (Pacheco et al., 2017) requiring the control of many degrees of freedom. Thus, the inconsistent findings comparing neural activity during VR and RW environments could be due to the nature of the task rather than the level of immersion, and more research is warranted to understand the degree to which these results can be generalized (Wang et al., 2020).

Additionally, Kober et al. (2021) only examined the neural activity differences over the motor cortex (i.e., C3, C4). Therefore, one key limitation in Kober et al. (2021) is that the regions that have been associated with sensory information processing during the performance of a motor skill (i.e., occipital, frontal, parietal) were not examined (Alsuradi et al., 2020; Ehinger et al., 2014; Magosso et al., 2019; Niedermeyer & Lopes, 2005). Such sensory information differences during the acquisition phase likely influence transfer of learning based on the practice specificity hypothesis (Proteau, 1992).

Observing neural activity differences, as measured by EEG, between a motor skill performed in immersive VR and the RW would not be surprising given that research investigating the fidelity between immersive VR and RW environments have shown behavioral differences between the two environments (Harris et al., 2020). For example, the haptic information (e.g., tactile, kinesthetic) differences between a task performed in VR compared to the RW is an issue that has been frequently discussed and has been shown to alter motor behavior (Harris et al., 2019; Whitwell et al., 2015; Wijeyaratnam et al., 2019). Covaci et al. (2015), for instance, found that when shooting a basketball in VR, compared to RW, there was a decrease in ball speed, an increase in the height of the ball release, and an increase in the height at which the ball entered the basketball hoop. Similar biomechanical differences due to different haptic information have been found between VR and RW in table tennis serve returns as well (Bufton et al., 2014). Changes in haptic information have been shown to alter cortical activity, specifically alpha oscillations within the frontal, parietal, and occipital regions (Alsuradi et al., 2020; Ehinger et al., 2014). Thus, due to the haptic information differences that have been proposed and shown to exist between a motor skill performed in VR and the RW (Bufton et al., 2014; Covaci et al., 2015; Harris et al., 2019; Whitwell et al., 2015; Wijeyaratnam et al., 2019), there are likely associated neural activity differences that could be observed during the practice of a motor task performed in VR and the RW.

Similarly, visual differences have also been proposed as another fidelity concern for immersive VR (Gray, 2019). This visual information issue has been revealed behaviorally as empirical evidence has found that depth perception and distance estimation during walking and reaching and grasping tasks are significantly less accurate in immersive VR compared to RW environments (Gonzalez-Franco et al., 2019; Mangalam et al., 2021). Though minimal research has been conducted to examine these visual differences during the performance of motor tasks in immersive VR from an EEG perspective, changes in visual stimuli would likely reveal cortical activity differences (Magosso et al., 2019; Niedermeyer & Lopes, 2005). Thus, in an accuracy task, such as golf putting which requires perceiving the depth of the target, visual processing differences would be expected given previous findings (Gonzalez- Franco et al., 2019; Mangalam et al., 2021). Such observations are likely to occur in the parietal region (Niedermeyer & Lopes, 2005), as an increase in alpha power at P3 has been shown in RW golf putting compared to putting in VR (Baumeister et al., 2010). Moreover, it is probable that alpha power differences would be found in the occipital region, as research has shown a decrease in alpha power as visual stimuli increases (Magosso et al., 2019; Mann et al., 1996). If an individual were to learn a motor skill in a VR environment while visual information differences persisted, it is predicted that the performance of the analogous motor skill within a RW environment (in which the visual information would be different) would be negatively influenced (Proteau, 1992).

Therefore, while immersive VR is becoming a popular tool to practice motor skills (Alsop, 2022), a large gap exists between the scientific evidence and the way in which VR is currently being used. Specifically, though there is relatively little research that has investigated the transfer of learning effects from immersive VR to RW environments, the current empirical evidence does support a positive transfer of learning for VR motor skill practice (Harris et al., 2020; Markwell et al., in press; Michalski et al., 2019; Oagaz et al., 2021). However, the learning effect following an extended amount of practice in addition to the associated neural similarities (or differences) are largely unknown. Furthermore, limited research exists about the psychological effects once an individual has been repeatedly exposed to VR practice. Hence, the purpose of this study was threefold: 1) to investigate transfer of learning effects following multiple days of VR golf putting practice and whether extended amounts of practice lead to increased VR specificity, 2) to examine the neural activity differences between VR and RW practice during the performance of the golf putting task, and 3) to determine the effects on intrinsic motivation following repeated practice within the VR environment. Without understanding the effect of VR exposure through an extended amount of practice, this technology may inadvertently be hindering the learning process. Thus, examining the transfer of learning and the associated neural activity and psychological factors over an extended period of practice not only contributes to the current scientific literature, but also provides significant value to those involved with developing and utilizing VR technology to enhance motor performance and learning.

There were five experimental hypotheses tested, three of which were based on motor performance and the associated neural activity data collected during practice and post-tests. The remaining two hypotheses were predictions regarding practice-related intrinsic motivation. Based on previous transfer of learning VR research (Harris et al., 2020; Markwell et al., in press; Michalski et al., 2019; Oagaz et al., 2021), it was predicted that performance in both practice groups will improve and no performance differences will exist between VR and RW practice during a posttest following one day of practice (hypothesis 1a). Specifically, hypothesis 1a predicted a significant main effect for test. However, considering previous findings reported in practice specificity research (Proteau, 1992), it was predicted that after an extended amount of practice, RW practice would result in significantly higher RW performance during the posttest on the fourth day compared to the group that practiced in VR (hypothesis 1b). More specifically, hypotheses 1b predicted a significant group x test interaction and the post hoc analysis would not reveal significant differences during test one but would reveal significant group differences during test four. This prediction is based on the understanding that differences exist between the available information in a RW and VR environment which affects the motor skill acquisition process (Mishra et al., 2021). To test this prediction, EEG was used to examine the neural activity differences during the practice phases of the golf putting task performed in VR and RW. Based on earlier research suggesting that sensory information differences resulted in behavioral changes (Bufton et al., 2014; Covaci et al., 2015), it was predicted that EEG measures would reveal neural differences between the VR and RW groups during the golf putting task (hypothesis 1c). Specifically, it was predicted that the analysis would reveal a significant main effect for group, the group x day interaction, group x ROI interaction, or group x day x ROI interaction. Lastly, in line with experiment one (Markwell et al., in press), it was predicted that VR practice would result in significantly higher intrinsic motivation following one day of practice (hypothesis 2a). Specifically, hypothesis 2a predicted a significant group x test x day interaction with post hoc analysis revealing higher motivation for the VR group during the day one posttest. However, based on literature investigating novelty and intrinsic motivation (Adachi et al., 2017; Jeno et al., 2019; Keller & Suzuki, 2014), it was predicted that no differences in motivation would exist between VR and RW practice following multiple days of practice (hypothesis 2b). Specifically, hypothesis 2b predicted a significant group x test x day interaction and the post hoc analysis would not reveal significant differences between groups during the day three posttest.

Method

Participants

To ensure the current study was properly powered, an a priori power analysis was performed using G*Power 3.1.9 (Faul et al., 2007; Faul et al., 2009). Given the novelty of this experiment and software used, the effect size used in the power analysis was based on the performance data collected during pilot testing. It is worth noting that pilot data can yield effect sizes that are imprecise (Leon et al., 2011). Based on the G*Power calculation with the effect size used from the performance data (i.e., accuracy) in the pilot data ($f = .210$), alpha = .05, power = .90, the projected sample size needed was approximately $N = 46$ for a within-between subject comparison (test family = F test; groups = 2; measurements = 4; correlation among repeated measures = 0.5; nonsphericity correction = 1). A total of 51 university students (males = 15; females = 36) between the ages of 18-34 years old ($M = 21.09$, $SD = 2.81$) volunteered to participate in the present experiment. Of the 51 students which volunteered for the study, a total of 43 (males = 10; females = 33) participants completed the experiment. Participants were informed that they would practice a golf putting task and that they will use VR; volunteers remained naïve to the purpose of the study. The mini simulator sickness questionnaire (MSSQ) was used to determine participants' susceptibility for motion sickness. Participants who scored 26 or higher were excluded from the study (n = 1). The University of Tennessee Institutional Review Board approved all methods and paperwork before the study began. Volunteers completed an informed consent prior to participation.

Task and Apparatus

The data collected for this experiment took place in a climate-controlled research laboratory. A golf putting task was used for both RW and VR practice conditions.

RW Golf Putting

The golf putting task was created on a carpeted surface (1.829 x 3.658 m) inside a research laboratory. The carpeted surface was green in color and carpet fibers resembled grass both in length and texture. Participants used a standard length (90 cm) golf putter to putt a regulation sized white golf ball towards a target on the carpeted surface that was the diameter of a standard golf hole (10.795 cm). There were three different starting lines from which the ball was putt (3 m, 2 m, 1 m; see figure 6). All trials during the pre- and post-tests were performed from the furthest distance (3 m; see figure 7). A web camera was fixed perpendicularly above the hole to capture the golf ball position. The camera application (Microsoft Corporation; version 2021.105.10.0) on an Alienware computer was used to capture the picture of the final resting golf ball position. Tracker software (version 6.0.1) was used to determine the x and y coordinates of the resting location of the golf ball.

VR Golf Putting

The Oculus Quest 2 (Facebook Reality Labs, Redmond, Washington, USA) VR headset was used to operate a custom virtual golf putting application built in Unity gaming engine (2022.1.4). The virtual golf putting course was designed to replicate the course which was utilized in the physical environment by the RW condition. The same shape, dimensions, and putting locations utilized in the RW condition were replicated in the virtual environment. Participants used a virtual golf putter to putt a virtual ball into a virtual hole while wearing the Oculus Quest 2 headset and holding one Oculus controller in their dominate hand. The VR environment was designed to mimic the environment of the RW laboratory. Haptic feedback was provided when the club head made contact with the golf ball, resulting in a slight vibration generated by the handheld controller. Auditory feedback in the form of the head of the putter

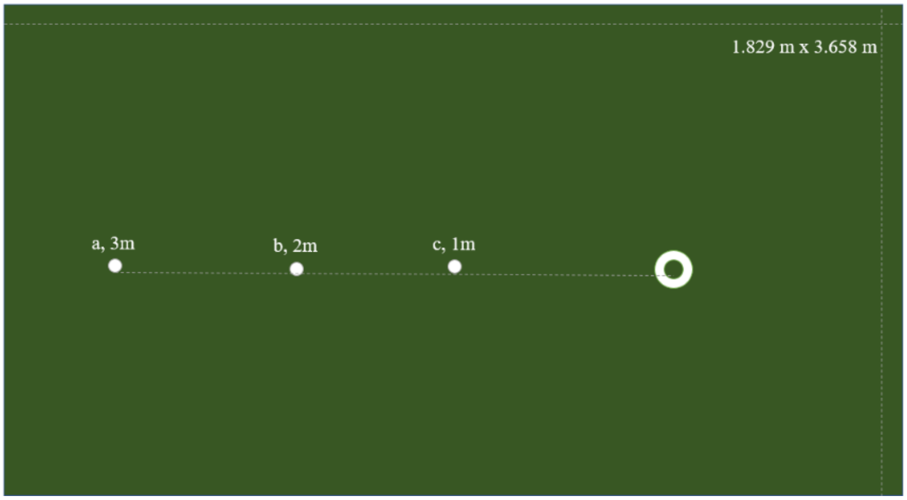

Figure 6. Practice phase putting green design and dimensions. The 60 trials were performed in a varied order (e.g., a,b,c,a,b,c,a,b,c…) from a distance of 3 meters, 2 meters, and 1 meter.

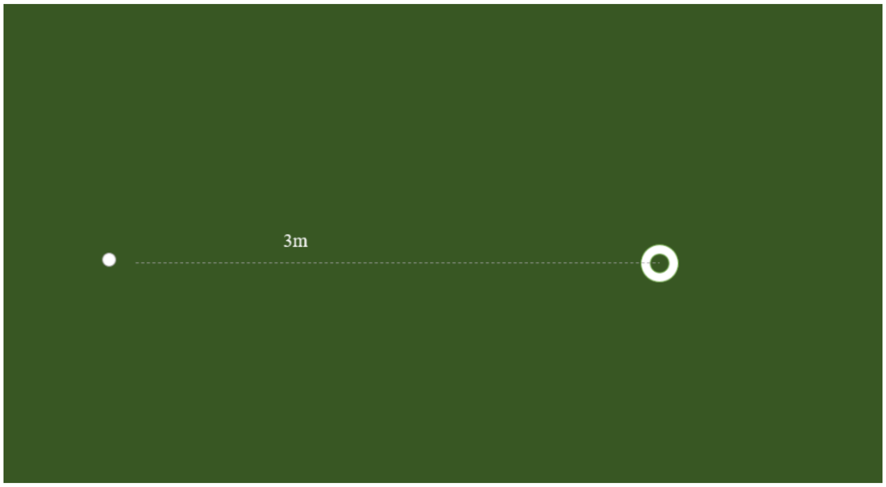

Figure 7. Test phase putting green design. All 10 trials were performed from a distance of 3 meters.

striking the golf ball was provided concurrently with the visual contact of the golf club striking the golf ball. No additional sound or features were provided to the learner as feedback for the duration of the study. Unity Experiment Framework (Brookes et al., 2019) was used to collect participant data and the application was programmed to automatically calculate and save golf putting performance data (i.e., radial error).

Procedure

Participants were randomly assigned into one of two groups (i.e., VR practice or RW practice). Each participant was involved in the study for four consecutive days. Days one, two, and three were identical and consisted of the IMI questionnaire, a golf putting pretest in both the RW and VR environments, and a golf putting practice phase. Day four included a golf putting posttest in both the RW and VR environments (see figure 8). The VR tests were included so that participants in both groups performed the same number of trials across the duration of the experiment. The tests in VR were not included in the analysis, given the research questions. The following are the abbreviations of the dependent measures which were measured during the course of the experiment: Intrinsic Motivation Inventory (IMI), radial error (RE), bivariate variable error (BVE), Electroencephalography (EEG).

On days one, two, and three, participants completed the IMI questionnaire to measure their intrinsic motivation prior to performing the practice phase of the experiment. Of the multiple subscales within the IMI, only the interest and enjoyment subscale was used as it is considered the self-reported measure of intrinsic motivation. More information about the IMI can be obtained from https://selfdeterminationtheory.org/intrinsic-motivation-inventory/. Additionally, the tense of the questionnaire to modified for pre- and post-questionnaires (e.g., I will enjoy this activity. I enjoyed this activity). Minor adaptions are encouraged to need research design needs (Ryan, 1994; Duncan & McKeachie, 2005; Choi et al., 2010) Participants were then provided instructions regarding how to perform the golf putting task, followed by a demonstration of the golf putting task for their respective group (e.g., VR or RW). The researcher provided the demonstration and all instructions for the duration of the experiment. After the participants received the instruction and demonstration, they performed a pretest in each environment (i.e., VR and RW) as described in Figure 8. The pretests were performed in a counterbalanced order across participants in an attempt to minimize order effects. To assess brain activity while performing the golf putting task, an EEG headset was placed on the participants' head prior to the initiation of the acquisition phase of the experiment. Once the headset was on the participants' head, the headset was calibrated to assure channel connectivity. Following the calibration, a 30 second baseline test was performed. Participants were instructed to sit as still as possible. The first 15 seconds of the baseline was performed with participants' eyes closed. The last 15 seconds was performed with the eyes open. In both groups, participants performed 60 trials per day for all three days of practice, for a total of 180 acquisition trials.

Participants practiced putting the golf ball from three different distances (i.e., 3 m; 2 m; 1 m, see Figure 6) in a serial order (e.g., abc, abc, abc…) until each participant accrued 60 trials each day. The researcher instructed the participant that the goal was to putt the golf ball as accurately as possible resulting in the golf ball coming to rest on top of the target located on the putting surface. Digital event markers were placed by the researcher in the recorded EEG signal at the initiation of the participants' backswing, and a second digital event marker was placed in the EEG signal once the ball came to a complete stop.

After the participants performed all the practice trials, the researcher removed the EEG headset and provided the participants with the same questionnaire given before the pretest.

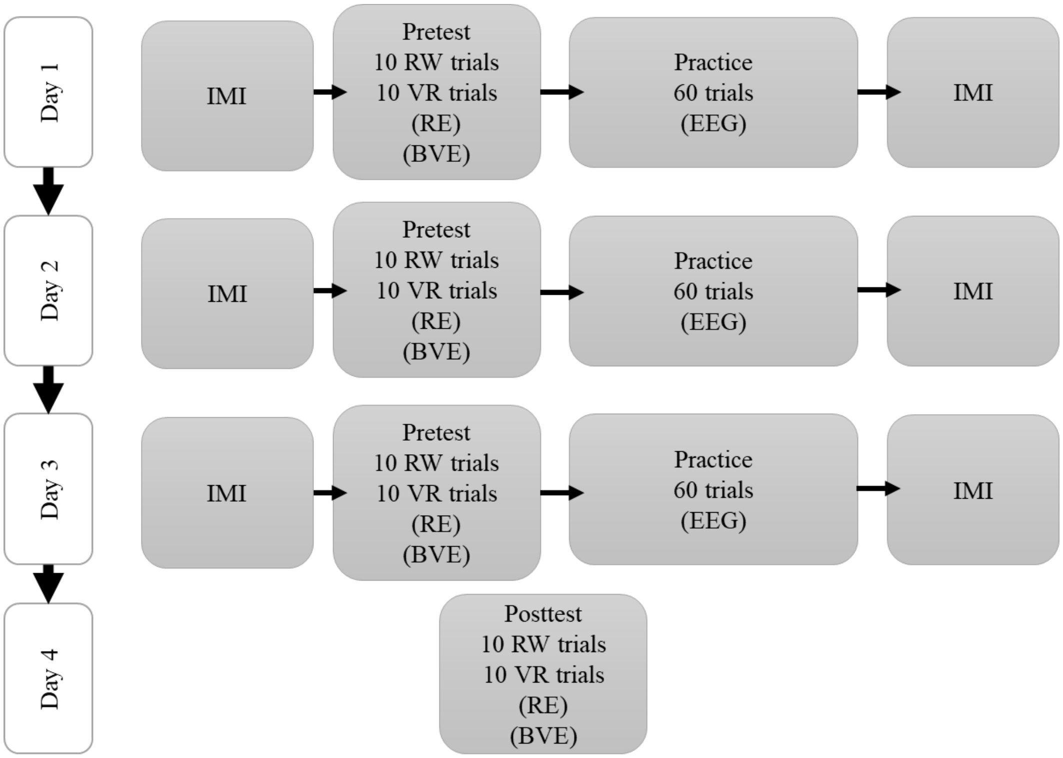

Figure 8. Schematic representation of the experimental design. Intrinsic Motivation Inventory (IMI), radial error (RE), bivariate variable error (BVE), Electroencephalography (EEG).

On day four of the study, participants returned to the lab and performed a posttest in both environments to assess motor learning retention and transfer.

Putting accuracy (i.e., radial error) and precision (i.e., bivariate variable error) were measured following each putting attempt. The center of the putting target was considered the origin of a two-dimensional grid with the coordinates 0,0. Radial error (RE) was calculated after each trial using the Pythagorean theorem to determine the Euclidean distance of the two closest points between the golf ball and the target (see figure 9).

$$RE = (x^2 + y^2)^{\frac{1}{2}}$$

To assess precision, bivariate variable error (BVE) was calculated by taking the square root of the squared mean distance of each trial from the centroid (*c*) of each block (*k*) of trials.

$$BVE = \left(\frac{1}{k}\sum_{i=1}^{k}(x_i - x_c)^2 + (y_i - y_c)^2\right)^{\frac{1}{2}}$$

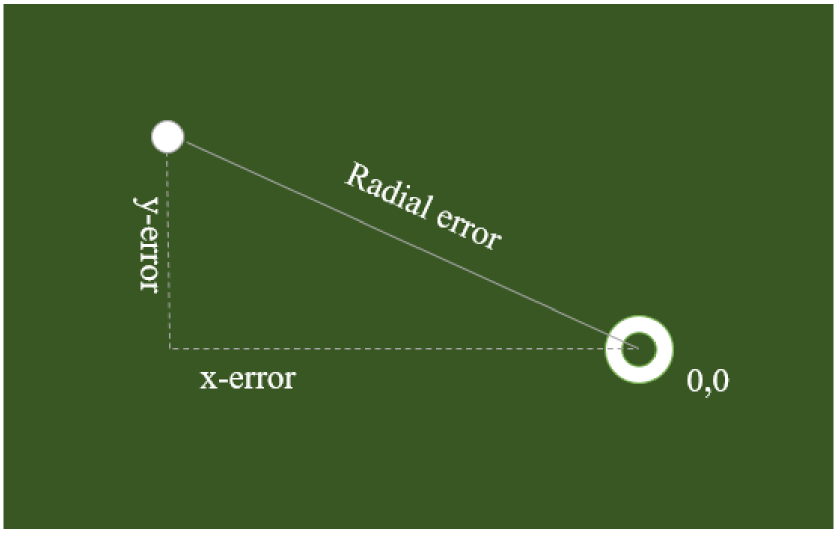

Figure 9. Example of golf ball accuracy measurement. The solid white circle represents the golf ball at a resting position. The open circle represents the target, which was at 0,0 coordinates. Accuracy was determined by the radial error (i.e., the distance of the closest point of the ball from the center of the target.)

EEG Recording and Band Power. Neural activity data was continuously collected using an Emotiv EPOC X EEG headset. This portable EEG device has 14 channels (AF3, AF4, F3, F4, F7, FC5, FC6, T7, T8, P7, P8, O1, O2), in addition to two references (P3, P4 locations). EEG data collected in each session was continuously recorded during the experiment for each practice session. After collection, EEG data was first sliced to include only the recordings between the first and second digital event related markers that were placed by the researcher. The first event related marker was placed by the researcher at the initiation of the participant's backswing. The second event related marker was designated by the researcher when the movement of the golf ball stopped. All sliced data, from each practice trial, were then merged into a single file to represent all slices in a single practice session. Each trial was approximately two seconds in duration. The EPOC X has a built-in pre-processing tool that includes a high-pass filter of 0.16 Hz and a low-pass filter of 43 Hz, digitization at 2048 Hz and filtering using a digital 5th order Sinc filter. Additionally, the software down samples to 128 Hz and uses the Emotiv Pro recording software system (version 3.2.3). After slicing and merging the trials, the data was put through high pass filtering set at 2 Hz for the DC offset and excluded low frequency noise. This was followed by a 35 Hz low bandpass filter, to exclude frequencies outside the specified range of interest. The EEG data was then normalized to baseline as the change in power relative to baseline. This was calculated by dividing each channel data by the same channel's average at baseline, then subtracting by 1 to get the difference from baseline, and then multiplying by 100 to get the result as a percentage from baseline. During the baseline, participants sat motionless with their eyes closed. The normalized data from each channel were then averaged into the identified four regions of interest (ROI): frontal (F3, F7, F4, F8), parietal (P3, P7, P4, P8), temporal (T7, T8), occipital (O1, O2). An independent component analysis

(ICA) was then used as a blind source separation (BSS) technique to remove artifacts. Based on the ICA, no artifacts were removed. A Fast Fourier Transform (FFT) was used for each trial. No windowing to taper the data was used. Following the FFT, data were then split into four bandwidth frequencies: Theta (4-8 Hz), Lower Alpha (8-10 Hz), Upper Alpha (10-12 Hz), and Beta (12-30 Hz). Then the average was computed at each ROI for each frequency band. Power was computed separately for each channel and trial (i.e., putt) as the product between each FFT coefficient and its complex conjugate (i.e., equivalent to amplitude squared). Each power value was then averaged to calculate the mean power for each frequency band at each ROI. All signal processing was performed using Python (version 3.9) software.

Data Analysis

Performance and Psychological Data. The data was analyzed using IBM SPSS Statistics version 28.0.0. A 2 (group: VR, RW) x 2 (test: pretest posttest), x 3 (day: one, two, three) mixed repeated measures analysis of variance (ANOVA) was used to assess the interest and enjoyment subscale of the IMI. Additionally, separate 2 (group) x 4 (test) ANOVAs were used to determine differences in accuracy (i.e., radial error) and precision (i.e., bivariate variable error) in the RW environment. Prior to analysis, Mauchly's test for sphericity was performed and Greenhouse-Geisser correction was applied when sphericity was violated.

EEG Band Power. Four separate 2 (group: RW, VR) x 3 (day) x 4 ROI (frontal; parietal; occipital; temporal) mixed repeated measures ANOVAs were used for each frequency (theta; lower alpha; upper alpha; beta). The 0.05 alpha level was adjusted and divided by four (band frequency). Statistical analyses were considered significant at $p \leq 0.0125$ given that any significant finding would support the hypothesis (for review, see Rubin, 2023). Greenhouse-

Geisser correction was applied when Mauchly's test for sphericity revealed sphericity was violated.

Results

Real World Performance Variables

Accuracy (Radial Error). A 2 (group) x 4 (test) repeated measures ANOVA was used to determine accuracy (i.e., radial error) differences between and within groups and tests. The analysis revealed a main effect for test, $F(3, 120) = 17.412$, $p < .001$, $\eta_p^2 = .303$. No significant differences were observed for the test x group interaction, $p = .495$, $\eta_p^2 = .020$, or between-group effects tests, $p = .519$, $\eta_p^2 = .010$. Post hoc analysis with Bonferroni adjustment was performed as a result of the significant main effect for test. The analysis revealed test two ($M = 56.32$, $SD = 18.77$), $p > .001$, three ($M = 54.27$, $SD = 16.81$), $p > .001$, and four ($M = 51.62$, $SD = 15.59$), $p > .001$, were significantly lower than test one ($M = 71.50$, $SD = 19.34$) (see figure 10). No other statistical differences were observed between tests.

Precision (Bivariate Variable Error). A 2 (group) x 4 (test) repeated measures ANOVA was conducted to determine precision (i.e., bivariate variable error) differences between and within the groups and tests. The analysis revealed a significant main effect for test, $F(3, 120) = 12.078$, $p < .001$, $\eta_p^2 = .232$. No significant differences were found for the group x test interaction, $p = .654$, $\eta_p^2 = .013$ or between groups, $p = 528$, $\eta_p^2 = .010$. The post hoc analysis with Bonferroni adjustment revealed test two ($M = 56.37$, $SD = 19.93$), $p > .001$, three ($M = 54.09$, $SD = 14.75$), $p > .001$, and four ($M = 55.08$, $SD = 15.86$), $p > .001$, were significantly lower than test one ($M = 70.05$, $SD = 17.23$) (see figure 11). No other statistical differences between tests were revealed.

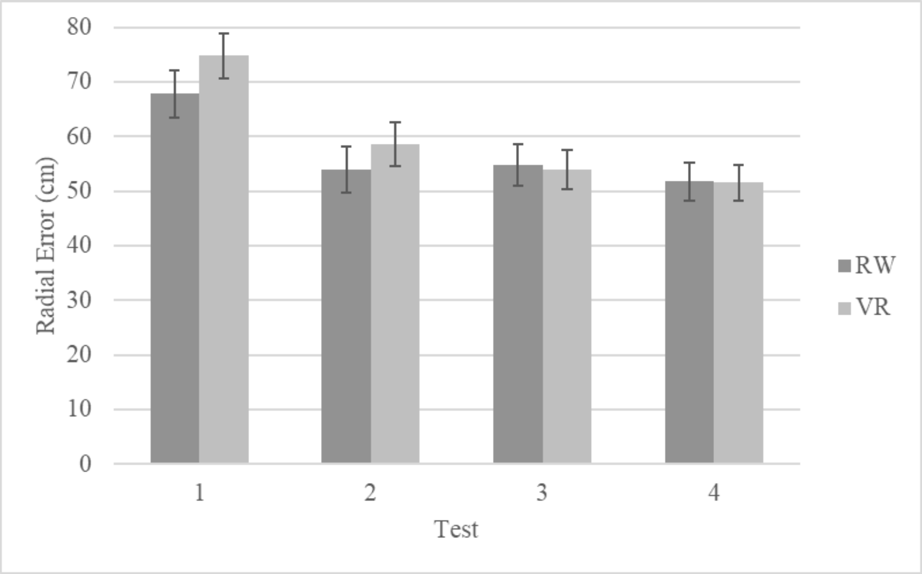

Figure 10. Accuracy Differences Across Tests. The error bars indicate standard error (SE). The following are the abbreviations used in the figure: real-world practice group (RW); virtual reality practice group (VR).

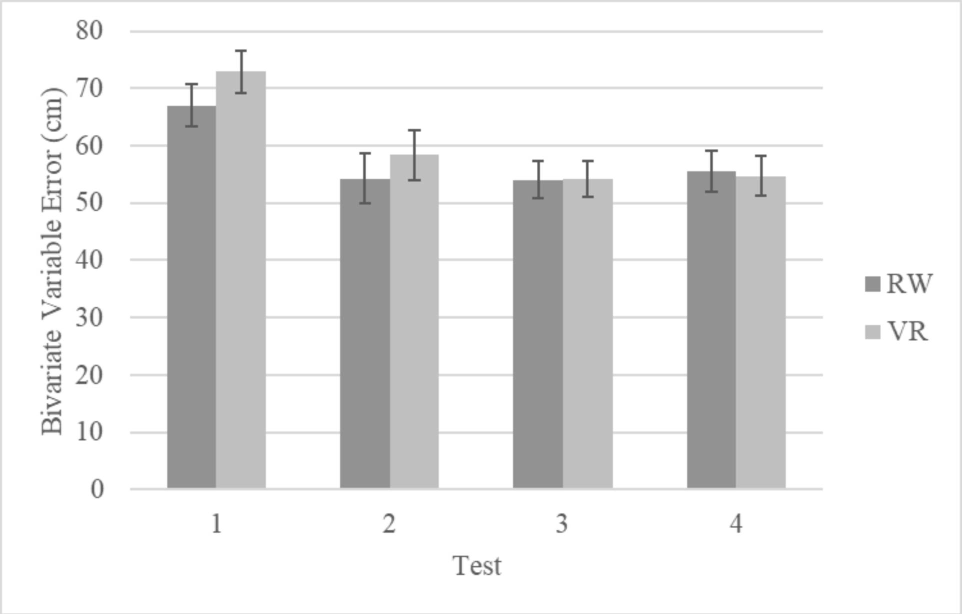

Figure 11. Precision differences between groups and across tests. The error bars indicate standard error (SE). The following are the abbreviations used in the figure: real-world practice group (RW); virtual reality practice group (VR).

Psychological Variables

Interest/Enjoyment. A 2 (group) x 2 (test) x 3 (day) repeated measures ANOVA was used to analyze differences between and within groups, tests, and across days. The analysis revealed a significant main effect for test, $F(1, 40) = 5.020$, $p = 0.031$, $\eta_p^2 = .112$. Post hoc analysis with Bonferroni adjustment indicated that, on average, the pretest (M = 5.002, SE = .162) scores were significantly lower than the posttests (M = 5.159, SE = .153) scores. Additionally, the analysis did not reveal a significant interaction between group x test, $p = .867$, $\eta_p^2 = .001$. No significant effects were found for day, $p = .189$, $\eta_p^2 = .041$, or the group x day interaction, $p = .476$, $\eta_p^2 = .018$ (see figure 12) Similarly, no significant main effects were found for the test x day interaction, $p = .161$, $\eta_p^2 = .045$, or the group x test x day interaction, $p = .776$, $\eta_p^2 = .006$. Furthermore, the between group analysis did not reveal a significant main effect, $p = .678$, $\eta_p^2 = .004$.

Neural Activity Variables

Theta Power. A 2 (group) x 3 (day) x 4 (ROI) repeated measures ANOVA was used to determine differences between groups and across days and ROI. No significant differences were revealed across day, $p = 0.185$, $\eta_p^2 = 0.059$. There was not a significant main effect for group $p = 0.184$, $\eta_p^2 = 0.062$, or the day x group interaction, $p = 0.241$, $\eta_p^2 = 0.050$. Furthermore, no significant differences were revealed for the ROI x group interaction, $p = 0.700$, $\eta_p^2 = 0.017$, or the day x ROI x group interaction, $p = 0.787$, $\eta_p^2 = 0.018$. A significant main effect was found for ROI, $p < 0.001$, $\eta_p^2 = 0.442$. Post hoc analysis with Bonferroni adjustment revealed that the parietal region was significantly larger than the frontal, $p < 0.001$, and temporal regions, $p < 0.001$.

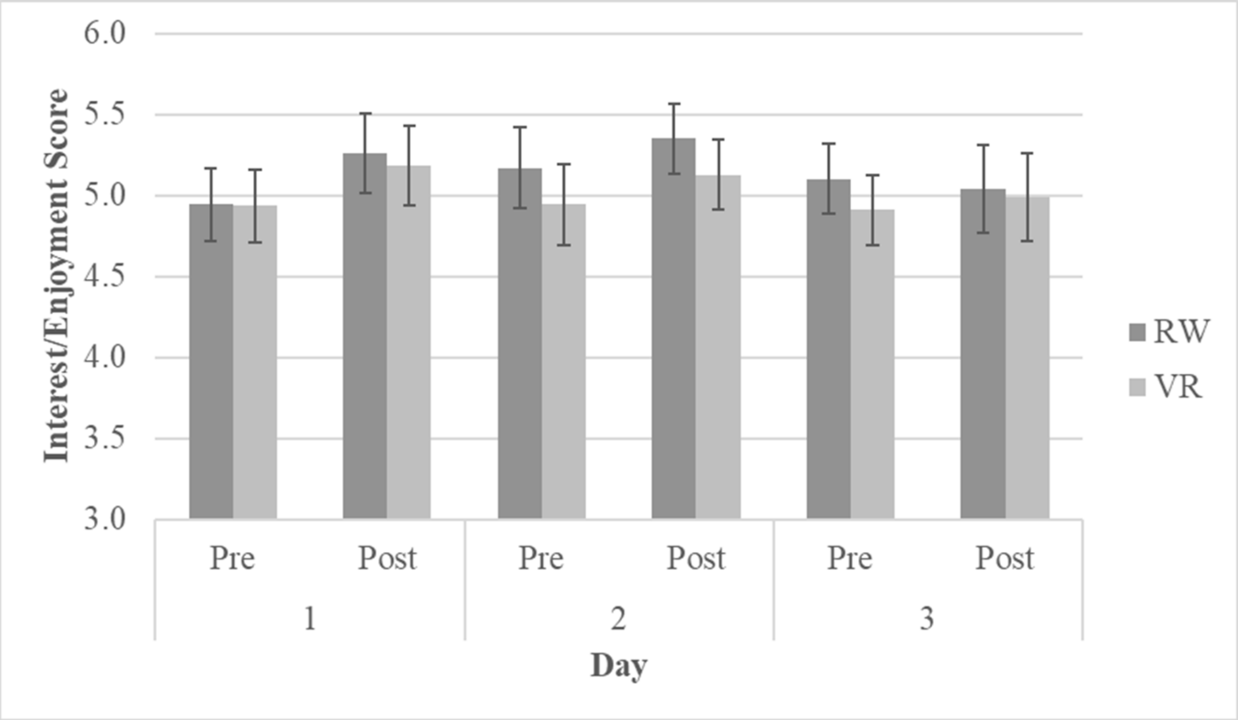

Figure 12. Interest & Enjoyment Differences Between Pre- and Posttest, Groups, and Across Days. The error bars indicate standard error (SE). The following are the abbreviations used in the figure: real-world practice group (RW); virtual reality practice group (VR).

Additionally, the analysis revealed the occipital region was significantly larger than the frontal region, $p < 0.001$. Lastly, the analysis did not reveal a significant main effect for the day x ROI interaction, $p = 0.902$, $\eta_p^2 = 0.013$ (see table 1).

Lower Alpha (8-10 Hz). A 2 (group) x 3 (day) x 4 (ROI) repeated measures ANOVA was used to determine differences between groups and across days and ROI. Mauchly's test indicated that the assumption of sphericity was violated for ROI ($\chi^2(5) = 21.179$, $p = .001$), therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .751$). No significant differences were revealed across day, $p = 0.169$, $\eta_p^2 = 0.061$. There was not a significant main effect for group $p = 0.501$, $\eta_p^2 = 0.016$, or the day x group interaction, $p = 0.526$, $\eta_p^2 = 0.023$. Additionally, no significant differences were revealed for the ROI main effect, $p = 0.350$, $\eta_p^2 = 0.037$, the ROI x group interaction, $p = 0.619$, $\eta_p^2 = 0.018$, day x ROI interaction, $p = 0.838$, $\eta_p^2 = 0.011$, or the day x ROI x group interaction, $p = 0.055$, $\eta_p^2 = 0.125$ (see table 1).

Alpha 2 (10-12 Hz). A 2 (group) x 3 (day) x 4 (ROI) ANOVA was used to test average power differences within the upper alpha frequency band. No significant main effects were revealed for day, $p = 0.263$, $\eta_p^2 = 0.048$, ROI, $p = 0.567$, $\eta_p^2 = 0.025$, or group, $p = 0.283$, $\eta_p^2 = 0.043$. Additionally, the day x condition main effect did not reveal a significant interaction, $p = 0.205$, $\eta_p^2 = 0.057$. There was not a significant main effect for the ROI x group interaction, $p = 0.245$, $\eta_p^2 = 0.050$, the day x ROI interaction, $p = 0.963$, $\eta_p^2 = 0.009$, or the day x ROI x group interaction, $p = 0.952$, $\eta_p^2 = 0.010$ (see table 1).

Beta. A 2 (group) x 3 (day) x 4 (ROI) repeated measures ANVOA was used to examine average power differences within the beta frequency band. Mauchly's test indicated that the

Table 1. ANOVA Results for Average Band Power.

Source	F	*p*	η_p^2
Theta			
Day	1.740	0.185	0.059
Group	1.855	0.184	0.062
ROI	22.143	0.001	0.442
Day x Group	1.459	0.241	0.050
ROI x Group	0.476	0.700	0.017
Day x ROI	0.362	0.902	0.013
Day x ROI x Group	0.527	0.672	0.018
Lower Alpha			
Day	1.835	0.169	0.061
Group	0.464	0.501	0.016
ROI	1.086	0.350	0.037
Day x Group	0.650	0.526	0.023
ROI x Group	0.520	0.619	0.018
Day x ROI	0.311	0.838	0.011
Day x ROI x Group	4.005	0.055	0.125
Upper Alpha			
Day	1.369	0.263	0.048
Group	1.201	0.283	0.043
ROI	0.680	0.567	0.025
Day x Group	1.634	0.205	0.057
ROI x Group	1.412	0.245	0.050
Day x ROI	0.238	0.963	0.009
Day x ROI x Group	0.266	0.952	0.010
Beta			
Day	1.771	0.180	0.062
Group	0.485	0.492	0.018
ROI	1.158	0.325	0.041
Day x Group	0.864	0.427	0.031
Day x ROI	0.220	0.898	0.008
ROI x Group	0.743	0.529	0.027
Day x ROI x Group	4.216	0.050	0.135

assumption of sphericity was violated for ROI ($\chi^2(5) = 20.249$, $p = .001$), therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .741$). There was not a significant main effect for day, $p = 0.180$, $\eta_p^2 = 0.062$, ROI, $p = 0.325$, $\eta_p^2 = 0.041$, or group, $p = 0.492$, $\eta_p^2 = 0.018$. A significant main effect for the day x group interaction was not revealed, $p = 0.427$, $\eta_p^2 = 0.031$. Furthermore, there was not a significant ROI x group interaction, $p = 0.529$, $\eta_p^2 = 0.027$, or a significant day x ROI interaction $p = 0.898$, $\eta_p^2 = 0.008$. There was not a significant main effect for the day x ROI x group interaction, $p = 0.050$, $\eta_p^2 = 0.135$ (see table 1).

Discussion

The use of VR technology has become popular for motor skill practice in various domains. Specifically, immersive VR headset use has exponentially increased over the last decade as software continues to develop and affordability improves (Alsop, 2022). As with any form of technology used to practice a skill, understanding how the technology impacts transfer of learning is critical (for a review, see Abernathy & Wood, 2001; Gray, 2019). The amount of empirical evidence that has investigated immersive VR and transfer of learning is minimal but growing, and multiple studies provide evidence that VR practice can facilitate performance improvements in RW environments (Harris et al., 2020; Markwell et al., in press; Michalski et al., 2019; Oagaz et al., 2021). In addition to this benefit, other research suggests that VR environments are more intrinsically motivating than traditional practice environments (Gray, 2019; Markwell et al., in press). However, little evidence exists to support positive transfer of learning to RW environments when the acquisition of a motor skill in VR spans several days. Therefore, the present study investigated the potential transfer of learning and intrinsic motivation effects between VR and RW practice after extended practice. Additionally, this study used EEG to compare neural activity during the two types of practice to better understand how surface brain activation patterns might differ when a learner practices a motor skill across multiple days in VR compared to practicing the same skill in the RW. The current study's results showed that both forms of practice resulted in significant RW performance improvements. Specifically, RW and VR practice improved RW golf putting accuracy by 24% and 31% and precision by 17% and 25%, respectively. However, no statistical differences were observed between the two groups. Furthermore, the results of the present experiment also demonstrated that no neural activity differences were observed between the two experimental groups, regardless of the frequency band or brain region. Finally, while the analysis revealed that intrinsic motivation scores were higher following practice compared to before practice, the analysis did not reveal changes in motivation across the days of acquisition, nor were motivational differences found between RW or VR practice. This study provides evidence that VR and RW practice result in similar motor learning benefits and that the benefits of VR practice are not diminished following an extended period of practice. Moreover, this study did not reveal differences in neural activity (i.e., frequency band power) or intrinsic motivation levels between the VR and RW practice conditions.

Performance Variables and Neural Activity

The results of the present study support hypothesis 1a that both VR and RW practice will lead to similar performance improvements within the RW environment. This finding is consistent with other studies investigating transfer of learning following immersive VR practice (Harris et al., 2020; Markwell et al., in press; Michalski et al., 2019; Oagaz et al., 2021). For example, Michalski et al. (2019) showed that practicing table tennis skills in VR led to greater RW performance improvements compared to no practice, as evidenced by the number of forehand, backhand, and alternating returns, as well as return accuracy. Similarly, in their second experiment, Harris et al. (2020) found that practicing a golf putt in both VR or RW environments significantly improved putting accuracy by 11.9% and 10.7%, respectively. No differences were observed between groups. Additionally, the findings reported by Harris et al. (2020) were further confirmed by experiment one of this dissertation (Markwell et al., in press), showing that VR and RW practice led to golf putting accuracy improvements at similar rates. The present study confirms previous findings that practicing a motor skill in VR facilitates positive transfer of learning and improves RW performance. Moreover, it adds to the findings of earlier experiments (Harris et al., 2020; Markwell et al., in press; Michalski et al., 2019; Oagaz et al., 2021) by providing evidence that VR practice improves accuracy (i.e., RE) and precision (i.e., BVE). Previous motor learning research investigating accuracy tasks has commonly measured accuracy and precision (e.g., Daou et al., 2018; Daou et al., 2019; Frank et al., 2015; Hancock et al., 1995) because both are regarded as essential measures of motor learning (Schmidt et al., 2018). To the author’s knowledge, experiment one of this dissertation (Markwell et al., in press) was the first experiment to assess precision during a study investigating immersive VR and transfer of learning. However, unlike the results of experiment two, experiment one of the present dissertation (Markwell et al., in press) did not find evidence of improved precision for VR or RW practice. The incongruent results reported in experiments one and two of the present dissertation are likely due to methodological differences between the two experiments. Specifically, experiment one used a constant practice design (e.g., a, a, a…), whereas the second experiment increased practice variability (i.e., putting distances) between each golf putting trial in the form of varied practice (e.g., a, b, c…).

A common theoretical explanation for the benefits of varied practice compared to constant practice is based on the variability of practice hypothesis (Moxley, 1979) stemming from experiments that have tested Schmidt's (1975) schema theory. In this theory, actions, as opposed to specific movements, are controlled by Generalized Motor Programs (GMPs). To perform a given action, a GMP is retrieved from the long-term memory. Then, movement specific parameters (e.g., overall muscles used, force of contraction, movement duration) are selected to determine how the action is executed. Different variations of the same action, requiring the same GMP but different parameters, exist depending on the performance situation. Constant practice only allows for the selection of the GMP and the *same* movement parameters. In contrast, varied practice allows for the repeated selection of the necessary GMP and *different* movement-specific parameters. The repeated selection of the GMP and different movement-specific parameters results in a greater abstract representation of the rules (i.e., schema) that are used to determine which parameters are required for different variations of a GMP. Thus, varied practice of a skill leads to the development of the GMP and schema, enhancing the ability to adapt to novel movement situations. However, the practice variability hypothesis, based on schema theory, primarily predicts how well a task will be performed during a transfer test (i.e., adapting to a novel movement context), rather than a retention test (Shea & Kohl, 1991, 1990).

The elaboration (Shea & Kohl, 1979) and action reconstruction hypothesis (Lee & Magill, 1985) are two hypotheses that stem from the research testing the contextual interference effect (for review, see Magill & Anderson 2021; Schmidt et al., 2018) that have been used to explain the practice variability benefit on retention (Shea & Kohl, 1990, 1991). The elaboration hypothesis (Shea & Kohl, 1979) predicts variations during the acquisition of a skill (i.e., varied practice), compared to no variations (i.e., constant practice), results in a more cognitively effortful practice due to comparing different cognitive strategies across skill variations. Subsequently, engaging with this more effortful practice has more detrimental effects on performance during the acquisition phase, but beneficial performance effects during retention and transfer (Shea & Kohl, 1979, 1990, 1991). Alternately, the action plan reconstruction hypothesis (Lee & Magill, 1985) assumes that an action plan is required to perform a motor skill. Variability, or interference, between task trials leads to the learner forgetting the action plan. Forgetting the action plan requires the learner to reconstruct the action plan for the subsequent trial. In contrast, practice without variability (i.e., constant practice) does not afford the reconstruction of the action plan, making practice less cognitively effortful, and allowing the learner to "go through the motions." Results from testing both hypotheses show that variability leads to a more effortful acquisition phase, but learning benefits emerge during post testing (Lee & Magill, 1985; Shea & Kohl, 1979, 1990, 1991). Given that a significant amount of research has shown motor learning benefits when variability is introduced between trials (e.g,. Shea & Kohl, 1990, 1991), the practice design differences (i.e., constant vs. varied) between experiments one and two likely explain the conflicting results reported in this dissertation.

Additionally, hypothesis 1b predicted that the RW group would outperform the VR group following an extended period of practice. Specifically, it was predicted that RW practice would outperform the VR practice group on the day four posttest. This prediction assumed that sensory information (e.g., haptic, visual, auditory, etc.) differences between the RW and VR environments differed (Mishra et al., 2021) and that these environmental differences, when practiced for multiple days, would hinder transfer of learning (Proteau, 1992) and ultimately result in greater improvements in the RW practice group. The present study's findings, however, did not support hypothesis 1b. Specifically, the results of experiment two did not reveal performance differences between the two practice groups. Rather, both RW and VR practice improved at similar rates, which is consistent with the previous studies (Harris et al., 2020; Markwell et al., in press; Oagaz et al., 2021) that have examined performance improvements following a single day of practice, compared to multiple days of practice and testing.

One explanation for both practice groups leading to similar rates in motor learning is that the sensory information provided within the VR environment across multiple days of practice was sufficient to elicit a transfer of learning effect. This finding suggests that the differences between the VR and RW environments were more similar than previously suggested (Mishra et al., 2021). The findings from the neural activity data collected during practice are congruent with the performance data. Specifically, no neural activity differences were observed regardless of the band frequency or brain region. If significant sensory informational differences existed between the two environments, it would be expected to observe neuro-activation differences during practice between the two groups (Alsuradi et al., 2020; Ehinger et al., 2014; Magosso et al., 2019). Furthermore, it would be expected to find transfer of learning differences between the practice groups if the VR group practiced in an environment in which the available sensory information during practice largely differed from the information available during the test (Proteau, 1992). However, in the present study, neither the motor learning data, nor the neural activation data during practice were found to differ between groups.

Previous studies investigating neural activity differences between immersive VR and RW environments have produced mixed results (Baumeister et al., 2010; Kober et al., 2021; Pacheco et al., 2017; Wang et al., 2020). For example, Baumeister et al. (2010) and Pacheco et al. (2017) similarly found that neural activation differed between VR and RW environments. In contrast, Kober et al. (2021) and Wang et al. (2020) did not find evidence of neural activity differences between RW and VR environments. However, the mixed findings appear to be due to the immersion level of the VR systems. The experiments that investigated immersive VR, as opposed to non-immersive, did not find neural activity differences during motor task performance (Kober et al., 2021; Wang et al., 2020). Specifically, during simple reaching tasks, Kober et al. (2021) and Wang et al. (2020) showed that the neural activity was similar between VR and RW environments. The current study extends those results (Kober et al., 2021; Wang et al., 2020) and suggests that neural activity similarities between immersive VR and RW environments may generalize to more complex tasks that require the control of multiple degrees of freedom (i.e., golf putting). Thus, these results suggest that immersive VR systems sufficiently replicate the sensory information available in a RW environment so that motor skill practice results in similar neural activity and motor learning over multiple days of practice.

Intrinsic Motivation

In addition to investigating transfer of learning and the associated neural activity effects and differences between VR and RW practice, the effects on intrinsic motivation between the two practice groups were also examined. Based on previous findings (Gray, 2019; Markwell et al., in press), it was predicted (hypothesis 2a) that VR practice would result in higher intrinsic motivation scores compared to RW practice following one day of acquisition. Contrary to this prediction, the results from the present study did not reveal higher intrinsic motivation for the VR practice group compared to the RW practice group. Other studies comparing intrinsic motivation levels in immersive VR and RW environments during classroom education (Friena & Ott, 2015; Liu et al., 2022; Makaransky et al., 2019) and aerobic exercise (Lui et al., 2019, 2021; Mouatt et al., 2020; Zeng et al., 2017) have provided evidence that immersive VR environments result in increased motivation compared to RW environments. Thus, unlike previous studies

(Friena & Ott, 2015; Liu et al., 2022; Makaransky et al., 2019; Markwell et al., in press; Mouatt et a., 2020; Zeng et al., 2017) which have shown that VR environments were more motivating compared to RW environments, the present experiment did not find evidence to support this conclusion.

One explanation for the lack of observed motivation differences between the practice groups in the present experiment could be due to the absence of “game-like” features within the VR application. In the current experiment, the VR application was designed specifically for this study and aimed to replicate the RW environment as much as possible. That is, the virtual environment was created to replicate the physical environment so that not only would the virtual golf putting green replicate the physical golf putting green, but the entire VR scene would appear to have the same layout as the physical laboratory (e.g., walls, desks, doors, golf putting green, etc.). Furthermore, the auditory feedback within the VR environment was also designed to replicate the physical environment. Specifically, the sound of the golf ball rolling, the golf club making contact with the golf ball, and the white noise within the laboratory were all recorded prior to the experiment and then uploaded to the VR application to provide auditory feedback as similar to the physical laboratory as possible. No additional features were included within the VR environment that were not native to the RW laboratory environment. The high degree of specificity and representativeness could have resulted in paradoxical effects. That is, designing the VR environment to replicate the RW environment so similarly could have led to a “specificity paradox” that benefits the user behaviorally by facilitating a positive transfer of learning effect. While at the same time, creating a virtual environment which was very similar to the physical environment may have masked the psychological benefits by making the environment less interesting and enjoyable, negating an increase in intrinsic motivation.

A recent review (Mouatt et al., 2020) examining studies investigating VR, motivation, and enjoyment during exercise concluded that while evidence is limited, certain features within VR may strongly influence the user's intrinsic motivation. For example, including avatars while exercising led to higher levels of motivation compared to not utilizing an avatar (Mouatt et al., 2020). However, in general, avatars that were competing against the user (i.e., competitive avatar) were found to increase motivation, whereas avatars that were providing positive feedback (i.e., cooperative avatar) were not found to increase motivation (Mouatt et al., 2020), suggesting certain aspects of these avatars influence motivation. A recent meta-analysis (Qian et al., 2020) investigating VR and exercise concluded that exercise performed in VR led to higher levels of interest and enjoyment, thereby increasing intrinsic motivation. However, such studies providing evidence for higher enjoyment and intrinsic motivation compared to non-VR exercise (e.g., Lui et al., 2019, 2021; Zeng et al., 2017) have used game-based applications that provide concurrent performance-based feedback, competitive avatars, and other features designed to enhance the perceived "game-like" environment. Therefore, in the present experiment, perhaps the lack of "game-like" features and a VR environment that was purposefully designed to replicate a research laboratory explains the lack of observed intrinsic motivation differences between the VR and RW practice groups. In other words, it is possible that the *features* included within an immersive VR environment, not immersive VR itself, create a more interesting and enjoyable practice environment, leading to higher levels of intrinsic motivation compared to traditional RW practice environments.

Lastly, it was hypothesized (i.e., hypothesis 2b) that intrinsic motivation would not differ between groups after three days of practice, due to decreased motivation levels for the VR group following multiple practice days. This prediction was based on previous research showing that novel environments could increase novelty and interest levels, thereby increasing intrinsic motivation (Adachi et al., 2017; Jeno et al., 2019). However, after repeated exposure to the environment, novelty and intrinsic motivation have been shown to decrease (Jensen & Konradsen, 2018; Keller & Suzuki, 2014). Intrinsic motivation levels did not differ after repeated exposure in the present experiment. In other words, motivation levels persisted across all three days of practice. However, as previously mentioned, the VR practice group did not report higher intrinsic motivation after the first day of practice. Thus, an initial increase in motivation for the VR group as a result of a “novelty effect” was not observed in the present experiment. Therefore, since higher motivation levels were not initially observed, it is difficult to conclude a potential “novelty effect” following repeated exposure to the VR environment. However, it is worth noting that a recent study tested a similar prediction in a classroom setting (Huang et al., 2020). In Huang et al. (2020), students participated in an undergraduate science lab using VR. The students were randomized into a high immersive group, a moderate immersive group, or a group that switched between high and moderate levels of immersion. Huang et al. (2020) showed that motivation levels persisted across multiple days after three days of exposure in the immersive VR environment. Huang et al. (2020) concluded that the increased motivation due to a “novelty effect” did not decrease after repeated exposure. However, a primary limitation of this study was that the VR groups were not compared to a non-VR group. Therefore, it is unknown how the observed persistence in motivation would have compared to a non-VR, traditional learning environment. Thus, while previous novelty research suggests that the increased motivation from novel environments fades following repeated exposure (Jensen & Konradsen, 2018; Keller & Suzuki, 2014), Huang et al. (2020), and the findings reported in the present experiment, provide empirical evidence that motivation levels in VR environments may persist following multiple days of practice. However, neither the present experiment nor Huang et al. (2020) provides evidence that immersive VR environments are more intrinsically motivating compared to RW environments regardless of the motivation persistence. Therefore, given the null results of the present experiment, further investigations are required to understand whether an increased motivation in immersive VR persists after multiple days of exposure.

Experiment Two Limitations and Conclusion

Empirical evidence from previous studies has shown that motor skill practice in immersive VR can result in RW performance improvements (Harris et al., 2020; Markwell et al., in press; Michalski et al., 2019; Oagaz et al., 2021). Moreover, experiment two of the present dissertation aimed to replicate the findings reported in experiment one (Markwell et al., in press), which showed that VR practice resulted in higher intrinsic motivation, and experiment two sought to address the limitations of previous investigations. That is, investigating the motor learning and intrinsic motivation differences after only one practice session was the primary limitation of experiment one (Markwell et al., in press). Thus, the present study investigated transfer of learning, neural activity, and intrinsic motivation over multiple days of VR practice. In line with previous studies (Harris et al., 2020; Oagaz et al., 2021), and the findings reported in experiment one of this dissertation (Markwell et al., in press), experiment two's results showed that VR practice resulted in similar motor learning improvements compared to RW practice following multiple days of practice. Furthermore, no neural activity differences were observed between the two forms of motor skill practice, consistent with similar investigations using simpler motor tasks (Kober et al., 2021; Wang et al., 2020). The results of the performance and neural activity data may suggest that the information available within the VR and RW environments is similar, given that no differences were revealed between motor behavior or neural activity. Lastly, and in contrast to experiment one of this dissertation (Markwell et a., in press), the findings of experiment two did not reveal that VR practice was more intrinsically motivating than RW practice. Instead, practice in either environment led to similar increases in intrinsic motivation.

While this study provided insights into how VR practice influences motor behavior, neural activity, and motivation, it is not without limitations, which should be addressed in future research. Specifically, one of the limitations in the present study are the null findings. The findings from the neural activity analyses are congruent with the performance data in the present experiment, and neural activity data from previous studies (Kober et al., 2021; Wang et al., 2020). Thus, these results could represent a true lack of differences (i.e., true negative) between the VR and RW practice groups. However, there is also the possibility of these results representing a false negative through type II error (Button et al., 2013; Vadillo et al., 2016). Thus, the findings of the present experiment should be interpreted cautiously as it does not confirm that the two practice groups' motor behavior, brain activity, and intrinsic motivation levels were the same. Rather, the findings of experiment two simply revealed that motor learning, the intrinsic motivation levels, and neural activity of the two groups were not different. Furthermore, it is important to note that this study examined one way in which neural activity during VR practice compared RW practice. However, there are many methods that can be used to examine brain activity during the acquisition of a motor skill. For example, due to logistical limitations, the present study only investigated neural activity during the *execution* of the golf putting task. Though, previous studies have shown how examining brain activity during the *preparation period* of a golf putting task can provide meaningful information when investigating motor learning (e.g., Daou et al., 2018). Similarly, neural activation differences have been shown to differ between the right and left hemisphere (e.g., Kiefer et al., 2014). While the present study did investigate four different brain regions of interest (i.e., frontal, temporal, occipital, parietal), the present study did not examine hemisphere differences between VR and RW practice. Finally, the present study used fixed frequency bands (e.g., 8-10 Hz for lower alpha) to examine cortical differences between groups. Recently, there has been recommendations to use individualized frequency bands for each participant (for review, see Parr et al., 2021) since the exact frequency range that specificizes a frequency band can vary between participants (Grandy et al., 2013). Thus, future work could extend the results of the present study by using other methods for comparing neural activation differences such as examining cortical activity during the motor preparation period, between the left and right hemispheres, and using individualized frequency bands.

Even with the aforementioned limitations, the present study provides a meaningful contribution to the current state of VR research. Overall, the results from experiment two empirically show that immersive VR technology adequately recreates RW sensory information and can improve motor skills within a real-world environment. These data further suggest that motor learning is not diminished relative to RW practice when practicing a motor skill in VR for multiple practice sessions. The findings from experiment two provide valuable information to those using immersive VR for learning or training purposes, scientifically investigating the effects of VR on human behavior, or developing software used in VR hardware.

General Discussion

Understanding how immersive VR elicits performance improvements in RW environments is imperative as VR technology grows. The theoretical explanations suggest that for learning to transfer from one environment to another, similarities must exist between the movement characteristics of the skill performed (Singley & Anderson, 1989; Thorndike, 1949) and the available information that is processed (Lee, 1988). Since few studies have tested transfer of motor learning from an immersive virtual practice environment to a non-virtual testing environment, experiments one (Markwell et al., in press) and two of the present dissertation investigated how practicing a motor skill in VR affects transfer of learning to a RW environment compared to practicing a motor skill in the RW. Both of the present experiments are consistent with previous findings (Harris et al., 2020; Michalski et al., 2019; Oagaz et al., 2021) and provide empirical evidence that VR practice results in a positive transfer of learning to a RW environment, leading to similar learning improvements compared to RW practice. Specifically, both experiments showed that RW golf putting accuracy improved as a result of VR practice. A key performance difference between the two experiments was that VR practice, and RW practice led to similar precision improvements during experiment two. Whereas during experiment one, neither VR nor RW practice improved golf putting precision. The higher variability between each trial during experiment two likely explains such differences, as intertrial variability has consistently been shown to enhance motor learning (e.g., Schmidt, 1975; Schmidt et al., 2019; Shea & Kohl, 1990, 1991).

In addition to providing evidence that VR practice facilitates a positive transfer of learning to RW environments, experiment one (Markwell et al., in press) also showed that VR practice led to higher levels of intrinsic motivation than RW practice. In contrast, experiment two did not show higher intrinsic motivation after VR practice. This null finding could be due to type II error, and this limitation warrants future investigation regarding how VR motor skill practice affects intrinsic motivation. However, the absence of increased motivation for the VR group during experiment two could have also been due to the differences between the VR environments used in experiments one and two. The VR environment in experiment two was designed with high specificity to represent the RW environment closely and therefore lacked "game-like" features. In contrast, the VR software used in experiment one (Markwell et al., in press) was Cloudlands VR Minigolf. This commercially available application was designed to replicate the dimensions of the RW putting green. However, inherent "game-like" physical features such as animation and physical fidelity existed which may have positively influenced interest and enjoyment within the VR group. Previous research investigating intrinsic motivation levels during immersive VR exercise has found that specific features within immersive VR affect users' interest and enjoyment levels, thereby influencing intrinsic motivation (Mouatt et al., 2020**).** Thus, the differences in the VR environments could have led to the differences in intrinsic motivation between experiments one and two. Despite the incongruent findings, previous studies have shown immersive VR to be more intrinsically motivating in classroom settings and during aerobic exercise (Friena & Ott, 2015; Liu et al., 2022; Makaransky et al., 2019; Mouatt et al., 2020; Qian et al., 2020). These results (Friena & Ott, 2015; Liu et al., 2022; Makaransky et al., 2019; Mouatt et al., 2020; Qian et al., 2020), combined with the findings from experiment one (Markwell et al., in press), suggest that motor skill practice in immersive VR has the potential to be an intrinsically motivating environment. However, given the limited evidence and the incongruent results between experiments one and two, future investigations are warranted to understand what is required for immersive VR environments to be more intrinsically motivating than traditional RW environments. Specifically, future experiments could manipulate certain features within VR environments during motor skill practice to understand which elements result in intrinsically motivating environments.

Lastly, previous reports have suggested that the available sensory information between VR and RW environments differs (Mishra et al., 2021). Research testing the practice specificity hypothesis (Proteau, 1992) and the transfer-appropriate processing hypothesis (Lee, 1988) suggests that transfer of learning is hindered if the available sensory information and the processing of that information differ between two environments. Experiment two investigated these potential differences using EEG to examine neural activity during the motor skill practice within each environment. Regardless of the analysis, no neural activity differences were found between the two conditions. Such findings expand upon previous studies that have compared brain activity during simpler motor tasks in immersive environments (Kober et al., 2021; Wang et al., 2020). Therefore, an immersive VR environment can provide sensory information representing the RW environment so that neural activity, as measured by EEG frequency band power, does not differ between the two environments. These findings are also congruent with the performance data reported in experiment two. If sensory information differed between the two environments, then it would be expected to observe motor learning differences between the RW and VR practice groups after an extended period of practice (Proteau, 1992). Based on the performance and neural activity results, immersive VR produces an environment in which the information available to the learner is similar to an analogous motor task performed in a traditional RW environment, as evidenced by neural activity during motor skill practice and motor behavior during retention and transfer tests.

In sum, based on the results reported in the present dissertation, immersive VR appears to be a viable option for creating an environment that produces similar perceptual and sensory information processing, facilitating motor skill acquisition and learning. Additionally, experiment one (Markwell et al., in press) and previous studies (Friena & Ott, 2015; Liu et al., 2022; Makaransky et al., 2019; Mouatt et al., 2020) suggest immersive VR is an intrinsically motivating option. Thus, the experiments within this dissertation provide empirical evidence that practitioners, coaches, and others alike can consider immersive VR as a tool to improve human learning and performance, and one that has the potential to be more motivating than traditional forms of practice. Although, before adopting VR technology to enhance human performance, it is critical to validate that such technology will facilitate a positive transfer of learning effect for that specific use and context. Of course, many questions still exist and are worth future investigations. For example, future studies should investigate how specific features included within immersive environments alter the user's intrinsic motivation. Moreover, understanding how much a fidelity type (e.g., biomechanical, affective, psychological, physical) can differ between the VR and RW environments and still result in a positive transfer of learning effect is essential as this hardware and software continue to develop (for a review, see Harris et al. (2019). Studying how algorithmic approaches can be best combined with VR to enhance motor learning will also be helpful as machine learning and artificial intelligence become more common in skill acquisition. Furthermore, investigating the integration of motor learning principles (e.g., practice variability, contextual interference, focus of attention, etc.) with VR would likely be fruitful for maximizing motor learning capabilities when utilizing this technology. Of course, however, these investigations are not necessarily unique to VR technology. Exploring how individuals can best learn motor skills precedes the present work by many decades and will be an ongoing question that both researchers and practitioners continue to explore for the years to come (Porter, 2008).

References

Abbatine, T. (2020). Is virtual reality (VR) training baseball's next performance edge? *Baseball America.* https://www.baseballamerica.com/stories/is-virtual-reality-vr-training-baseballs-next-performance-edge/.

Abe, M., Schambra, H., Wassermanm, E. M., Luckenbaugh, D., Schweighofer, N., & Cohen, L. G. (2011). Reward improves long-term retention of a motor memory through induction of offline memory gains. *Current Biology, 21,* 557-562.

Abernathy, B. & Wood, J. M. (2001). Do generalized visual training programmes for sport really work? An experimental investigation. *Journal of Sports Science, 19,* 203-222.

Adachi, P. J., Ryan, R., Frye, J., McClung, D., & Rigby, C. (2017). "I can't wait for the next episode!" investigating the motivational pull of television dramas through the les of self-determination theory. *Motivation Science, 4,* 78-94.

Adcock, R. A., Thangavel, A., Whitfield-Grabrieli, S., Knutson, B.,Gabrieli, J. D. (2006). Reward-motivated learning: Mesolimbic activation precedes memory formation. *Neuron, 50,* 507-517.

Alsop, T. (2022, May). *AR/VR headset shipments worldwide 2019-2023.* Statista. https://www.statista.com/statistics/653390/worldwide-virtual-and-augmented-reality-headset-shipments/

Anderson, B. J., Li, X., Alcantara, A. A., Isaacs, K. R., Black, J. E., & Greenouch, W. T. (1994). Glial hypertrophy is associated with synaptogenesis following motor-skill learning, but not with angiogenesis following exercise. *Glia, 11,* 73-80.

Appelbaum, G. L. & Erickson, G. (2018). Sports vision training: A review of the state-of-the-art in digital training techniques. *International Review of Sport and Exercise Psychology, 11,* 160-189.

Bacelar, M. F., Parma, J. O., Murrah, W. M., Miller, M. W. (2022). Meta-analyzing enhanced expectancies on motor learning: positive effects but methodological concerns.

Becker, K. & Smith, P. J. K. (2013). Age, task complexity, and sex as potential moderators of attentional focus effects. *Perceptual and Motor Skills, 117,* 1172-1186.

Bideau, B., Kulpa, R., Vignais, N., Brault, S., Multon, F., & Craig, C. (2010). Using virtual reality to analyze sports performance. *IEEE Computer Graphics and Applications, 30,* 14-21.

Broadbent, D. P., Causer, J., Williams, A. M., & Ford, P. R. (2015). Perceptual-cognitive skill training and its transfer to expert performance in the field: future research directions. *European Journal of Sport Science, 15,* 322-331.

Brouwer, A. M., Neerincx, M. A., & Kallen, V. (2011). EEG alpha asymmetry, heart rate variability and cortisol in response to virtual reality induces stress. *Journal of CyberTherapy & Rehabilitation, 4,* 21-34.

Bufton, A., Campbell, A., Howie, E., Straker, L. (2014). A comparison of the upper limb movement kinematics utilized by children playing virtual and real table tennis. *Human Movement Science, 38,* 84-93.

Burdea, G. C. & Coiffet, P. (2003). *Virtual Reality Technology.* John Wiley & Sons.

Cabral, D. A., Wilson, A. E., Miller, M. W. (2022). The effect of implicit on motor performance under psychological pressure: A system review and meta-analysis. *Sport, Exercise, & Performance Psychology, 11,* 245-263.

Chen, K. B., Kimmel, R. A., Batholomex, A., Ponto, K., Gleicher, M. L., & Radwin, R. G. (2014). Manually locating physical and virtual reality objects. *Human Factors, 56*, 1163-1176.

Chirico A., & Gaggioli A. (2019). When virtual feels real: comparing emotional responses and presence in virtual and natural environments. *Cyberpsychology, Behavior, and Social Networking, 22,* 220–226.

Choi, J., Mogami, T. & Medalia, A. (2010). Intrinsic Motivation Inventory: an adapted measure for schizophrenia research. Schizophrenia Bulletin, 36, 966–976.

Cipresso, P., Giglioli, I. A. C., Raya, M. A., & Riva, G. (2018). The past, present, and future of virtual and augmented reality research: A network and cluster analysis of the literature. *Frontiers in Psychology, 9,* 2086.

Cochran, S. M., Aiken, C. A., Rhea, C. K., & Raisbeck, L. D. (2021). Effects of an external focus of attention and target occlusion on performance in virtual reality. *Human Movement Science, 76,* 102753.

Ćosić K., Popović S., Kukolja D., Horvat M., & Dropuljić B. (2010). Physiology-driven adaptive virtual reality stimulation for prevention and treatment of stress related disorders. *Cyberpsychology, Behavior, and Social Networking, 13*, 73–78.

Covaci A., Olivier A. H., & Multon F. (2015). Visual perspective and feedback guidance for VR free-throw training. *IEEE Computer Graphics and Applications, 35,* 55–65.

Cruiz-Neira, C., Sandin, D. J., DeFanti, T. A., Kenyon, R. V., & Hart, J. C. (1992). The CAVE: Audio visual experience automatic virtual environment. *Communications of the ACM, 35,* 64-72.

Daou, M., Hutchison, Z., Bacelar, M., Rhoads, J. A., Lohse, K. R., & Miller, M. W. (2019). Learning a skill with the expection of teaching it ipairs the skill's execution under psychological pressure. *Journal of Experimental Psychology Applied, 25,* 219-229.

Daou, M., Lohse, K. R., & Miller, M. W. (2018). Expecting to teach enhances motor learning and information processing during practice. *Human Movement Science, 49,* 336-345.

Davids K., Williams A. M., & Williams J. G. (2005). *Visual Perception and Action in Sport.* Routledge.

De Mello Monteiro, C. D., Massetti, T., Dias da Silva, T., van der Kamp, J., Carlos de Abreu, L., Leone, C., & Savelsbergh, G. J. P. (2014). Transfer of motor learning from virtual to natural environments in individuals with cerebral palsy. *Research in Developmental Disabilities, 35,* 2430-2037.

Demers, M., Fung, K., Subramanian, S., Lemay, M., & Robert, M. T. (2021). Integration of motor learning principles into virtual reality interventions for individuals with cerebral palsy: Systematic review. *JMIR Serious Games, 9*, e23822.

Diemer J., Alpers G. W., Peperkorn H. M., Shiban Y., Mühlberger A. (2015). The impact of perception and presence on emotional reactions: a review of research in virtual reality. *Frontiers in Psychology, 6.*

Drew, S. A., Awad, M. F., Armendariz, J. A., Gabay, B., Lachica, I. J., & Hinkel-Lipsker, J. W. (2020). The trade-off of virtual reality training for dart throwing: A facilitation of perceptual-motor learning with a detriment to performance. *Frontiers in Sports and Active Living.*

Eadie, A. S., Gray, L. S., Carlin, P., & Mon-Williams, M. (2000). Modelling adaptation effects in vergence and accommodation after exposure to a simulated virtual reality stimulus. *Ophthalmic and Physiological Optics, 20,* 242-251.

Ericsson, K. A., Krampe, R. T., & Tesch-Romer, C. (1993). The role of deliberate practice in the acquisition of expert performance. *Psychological Review, 100,* 363-406.

Fowler, C. (2015). Virtual reality and learning: Where is the pedagogy? *British Journal of Educational Technology, 46,* 412–422.

Frank, C., Land, W. M., & Schack, T. (2016). Perceptual-Cognitive changes during motor learning: The influence of mental and physical practice on mental representation, gaze behavior, and performance of a complex action task. *Frontiers in Psychology, 6*, 1981.

Frederiksen, J. G., Sørensen, S. M. D., Konge, L., Svendsen, M. B. S., Nobel-Jørgensen, M., Bjerrum, F., & Andersen, S. A. W. (2020). Cognitive load and performance in immersive virtual reality versus conventional virtual reality simulation training of laparoscopic surgery: A randomized trial. *Surgical Endoscopy, 34*, 1244–1252.

Gerig, N., Mayo, J., Baur, K., Wittmann, F., Riener, R., & Wolf, P. (2018). Missing depth cues in virtual reality limit performance and quality of three dimensional reaching movements. *PLoS ONE, 13,* e0189275.

Golomb, M. R., McDonald, B.C., Warden, S. J., Yonkman, J., Saykin, A. J., Shirley, B., Huber, M., Rabin, B., AbdelBaky, M., Nwosu, M. E., Barkat-Masih, M., & Burdea, G. C. (2010). In-home virtual reality videogame telerehabilitation in adolescents with hemiplegic cerebral palsy. *Archives of Physical Medicine and Rehabilitation, 91,* 1-8.

Gonzalez-Franco, M., Abtahi, P., & Steed, A. (2019). "Individual differences in embodied distance estimation in virtual reality", in IEEE conference on virtual reality and 3D user interfaces (VR), Oaska, Japan, March 23-27, 2019 (Piscataway, NJ: IEEE), 941-943.

Gray, R. (2002). Behavior of college baseball players in a virtual batting task. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 1131–1148.

Gray, R. (2017). Transfer of training from virtual to real baseball batting. *Frontiers in Psychology, 8*, 2183.

Gray, R. (2019). Virtual environments and their role in developing perceptual-cognitive skills in sports. In A. M. Williams & R. C. Jackson (Eds.). *Anticipation and decision making in sport* (pp. 342-358). Routledge.

Gray, R. (2020). Sport training technologies. In N. J. Hodges & M. A. Williams, M. A. (Eds.). *Skill acquisition in sport* (pp.). Routledge.

Gray, R., & Regan, D. (1999). Motion in depth: Adequate and inadequate simulation. *Perception & Psychophysics*, *61*, 236-245.

Gruber, M. J., Gelman, B. D., Ranganath, C. (2014). States of curiosity modulate hippocampus-dependent learning via the dopaminergic circuit. *Neuron, 22*, 486-496.

Guadagnoli, M. & Lee, T. (2004). Challenge point: A framework for conceptualizing the effects of various practice conditions in motor learning. *Journal of Motor Behavior, 36*, 212-224.

Haar, S., Sundar, G., & Faisal, A. A. (2021). Embodied virtual reality for the study of RW motor learning. *PLoS ONE, 16*, e0245717.

Hancock, G. R., Butler, M. S., Fischman, M. G. (1995). On the problem of two-dimensional error scores: measures of analyses of accuracy, bias, and consistency. *Journal of Motor Behavior, 27,* 241-250.

Harris, D., Bird, J., Smart, P., Wilson, M., & Vine, S. (2020a). A framework for the testing and validation of simulated environments in experimentation and training. *Frontiers in Psychology, 11,* 605.

Harris, D., Buckingham, G., Wilson, M. R., Brookes, J., Mustaq, F., Mon-Williams, M., & Vine, S. J. (2020b). Exploring sensorimotor performance and user experience within a virtual reality golf putting simulator. *Psychology of Sport & Exercise, 50*, 101721.

Harris, D., Buckingham, G., Wilson, M., & Vine, S. (2019). Virtually the same? How impaired sensory information in virtual reality may disrupt vision for action. *Experimental Brain Research, 237,* 2761-2766.

Harris, D., Hardcastle, K. J., Wilson, M. R., & Vine, S. J. (2021). Assessing the learning and transfer of gaze behaviours in immersive virtual reality. *Virtual Reality, 25,* 961-973.

Harris, D., Wilson, M., Vine, S. (2020c). Development and validation of a simulation workload measure: the simulation task load index (SIM-TLX). *Virtual Reality, 24,* 557-566.

Hays, R. T., Jacobs, J. W., Prince, C., & Salas, E. (1992). Flight simulator training effectiveness: A meta-analysis. *Military Psychology, 4,* 63-74.

Heilig, M. L. (1962). Sensorama Simulator. Google Patents.

Hernandez, H. A., Khan, A., Fay, L., Roy, J., & Biddiss, E. (2018). Force resistance training in hand grasp and arm therapy: Feasibility of a low-cost videogame controller. *Games for Health Journal, 7,* 277-287.

Hornsey, R. L., Hibbard, P. B., & Scarfe, P. (2020) Size and shape constancy in consumer virtual reality. *Behavior Research Methods, 52,* 1587-1598.

Hunicke, R. LeBlanc, M., & Zubek, R. (2004). “MDA: formal approach to game design and game research,” in *Proceedings of the Challenges in Game AI Workshop, 19th National Conference on Artificial Intelligence,* San Jose, CA.

Jennett, C., Cox, A., Cairns, A. L., & Dhoparee, S. (2008). Measuring and defining the experience of the immersion in Games. *International Journal of Human-Computer Studies, 66,* 641-661.

Jeno, L. M. Vandvik, V., Eliassen, S. Grytnes, J. (2019). Testing the novelty effect of an m-learning tool on internalization and achievement: A Self-Determination Theory Approach. *Computers & Education, 128,* 398-413.

Juliano, J. M., & Liew, S. K. (2020). Transfer of motor skill between virtual reality viewed using a head-mounted display and conventional screen environments. *Journal of Neuroengineering and Rehabilitation, 17.*

Jung, Y. (2011). Understanding the role of sense of presence and perceived autonomy in users continued use of social virtual worlds. *Journal of Computer-Mediated Communication, 16,* 492–510.

Keller, J. N. & Suzuki, K. (2004). Learner motivation and E-learning designs: A multinationally validated process. *Journal of Education Media, 29,* 229-239.

Kempermann, G., Kuhn, H. G., & Gage, F. H. (1997). More hippocampal neurons in adult nice living in an enriched environment. *Nature, 368,* 493-495.

Kiefer, A. M., Cremades, J. G., & Myer, G. D. (2014). Train the brain: Novel electroencephalography data indicate links between motor learning and brain adaptations. *Journal of Novel Physiotherapy, 4,* 198.

Kirschner, P. A. (2002). Cognitive load theory: Implications of cognitive load theory on the design of learning. *Learning and Instruction, 12,* 1-10.

Kocian, D. (1997). A visually coupled airborne system simulator (VCASS) – An approach to visual simulation. Presented at IMAGE Conference. Phoenix, AZ. https://apps.dtic.mil/sti/citations/ADA039999

Kozak, J. J., Hancock, P. A., Arthur, E. J., & Chrysler, S. T. (1992). Transfer of training from virtual reality. *Ergonomics, 36,* 777-784.

Kramida, G. (2016). Resolving the vergence-accommodation conflict in head-mount displays. *IEEE Transactions on Visualization and Computer Graphics, 22,* 1912-1931.

Krueger, Myron W., Hinrichsen, K., & Giofriddo, T. (1985). VIDEOPLACE — An Artificial Reality. In: *Proceedings of the SIGCHI conference on Human factors in computing systems series CHI '85*. San Francisco, California, United States: Association for Computer Machinery (ACM).

Kumar, A., Tanaka, Y., Grigoriadis, A., Grigoriadis, J., Trulsson, M., & Svensson, P. (2017). Training-induced dynmaics of accuracy and precision in human motor control. *Scientific reports, 7,* 67984.

Lee, T. D. (1988). Transfer-appropriate processing: A framework for conceptualizing practice effects in motor learning. In: Meijer, O.G, Roth, K. (eds.). Advances in psychology. vol. 50. Amsterdam: North Holland, pp.201–215.

Levac, D. E., Huber, M. E., & Sternad, D. (2019). Learning and transfer of complex motor skills in virtual reality: A perspective review. *Journal of neuroengineering and rehabilitation, 16.*

Levin, M. F., Weiss, P. L., & Keshner, E. A. (2015). Emergence of virtual reality as a tool for upper limb rehabilitation: Incorporation of motor control and motor learning principles. *Physical Therapy, 95,* 415-425.

Lohse, K., Boyd, L., Hodges, N. (2016). Engaging environments enhance motor skill learning in a computer gaming task. *Journal of Motor Behavior, 48,* 172-182.

Loomis, J. & Knapp, J. (2003). Visual perception of egocentric distance in real virtual environments. In L. J. Hettinger & M. W. Hass (Eds.), *Virtual and adaptive environments: Applications, implications, and human performance issues* (pp. 21-46). Lawrence Erlibaum Associates Publishers.

Lopes, P. You, S. Cheng, L.P. Marwecki, S., & Baudisch, P. (2017). Providing haptics to walls & heavy objects in virtual reality by means of electrical muscle stimulation. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, Denver, CO. USA, 6–11, May. pp. 1471–1482.

Magdalon, E. C., Michaelsen, S. M., Quevedo, A. A., & Levin, M. F. (2011). Comparison of grasping movements made by healthy subjects in a 3-dimensional immersive virtual versus physical environment. *Acta Psychologica, 138,* 126–134.

Magill, R. A., & Hall, K. G. (1990). A review of the contextual interference effect in motor skill acquisition. *Human Movement Science, 9*, 241–289.

Magill, R. A., & Anderson, D. I. (2021). *Motor Learning and Control: Concepts and Applications.*

Mangalam, M., Yarossi, M., Furmanek, M. P., & Tunik, E. (2021). Control of aperture closure during reach-to-grasp movements in immersive haptic-free virtual reality. *Experimental Brain Research, 239,* 1651-1665.

Markwell, L. T., Strick, A. J., Porter, J. M. (2022). No fans, no problem: An investigation of audience effects on shooting performance in professional basketball. *Journal of Motor Learning and Development, 10,* 212-223.

Markwell, L. T., Velten, J. R., Partridge, J. A., & Porter, J. M. (in press). Virtual motivation: The psychological and transfer of learning effects of immersive virtual reality practice. *Journal of Motor Learning and Development.*

McKay, B., Jussien, J., Vinh, M., Mir-Orefice, A., Brooks, H., & Ste-Marie, D. M. (2022). Meta-analysis of the reduced relative feedback frequency effect on motor learning and performance. *Psychology of Sport and Exercise, 61,* 102165.

McKeachie, W.J., Pintrich, P.R., Lin, Y.G. & Smith, D. (1986). Teaching and learning in the college classroom: a review of the research literature. Ann Arbor: University of Michigan, National Center for Research to Improve Postsecondary Teaching and Learning.

Meehan, M., Insko, B., Whitton, M. C., & Brooks, F. P. (2002). Physiological measures of presence in stressful virtual environments. *ACM Transactions on Graphics, 21.*

Michalski, S. C., Szpak, A., & Loetscher, T. (2019). Using virtual environments to improve RW motor skills in sports: A systematic review. *Frontiers in Psychology, 10.*

Michalski, S.C., Szpak, A., Saredakis, D., Ross, T.J., Billinghurst, M., & Loetscher, T. (2019). Getting your game on: Using virtual reality to improve real table tennis skills. *PLoS ONE, 14,* e0222351.

Miles, H. C., Pop, S. R., Watt, S. J., Lawrence, G. P., John, N. W., Perrot, V., & Mestre, D. R. (2013). Investigation of a virtual environment for rugby skills training. IEEE Symposium conducted at the meeting of the Cyberworlds.

Miller, R. B. (1954). Psychological considerations in the design of training equipment. WADC Tech Report 554-563. Wright-Patterson AFB: Wright Air Development Centre, Aero Medical Laboratory.

Moghimi, M., Stone, R., & Rotshtein, P. (2020). Affective recognition in dynamic and interactive virtual environments. *IEEE Transactions on Affective Computing, 11,* 45-62.

Moghimi, M., Stone, R., Rotshtein, P. & Cooke, N. (2016). Influencing human affective responses to dynamic virtual environments. *Presence, 25,* 81-107.

Mon-William, M., Tresilian, J. R., McIntosh, R. D., & Milner, D. A. (2001). Monocular and binocular distance cues: Insights from visual form agnosia I (of III). *Experimental Brain Research,* 139, *127-136.*

Mon-Williams, M. & Tresilian, J. R. (1999). Some recent studies on the extraretinal contribution to distance. *Perception, 28,* 167-181.

Nacke, L. & Lindley, C. A. (2008). Flow and immersion in first-person shooters: measuring the player's gameplay experience. Proc of the 2008 ACM Conference on Future Play: Research, Play, Share, pp. 81-88, November 2008.

O'Brien, H. L. & Toms, E. (2008). What is user engagement? A conceptual framework for defining user engagement with technology. *Journal of the American Society for Information Science and Technology, 59,* 938-955.

Oagaz, H., Schoun, B., & Choi, M. (2021). Performance improvement and skill transfer in table tennis through training in virtual reality. *IEEE Transactions on visualization and computer graphics.*

Ottosson, S. (2010). Virtual reality in the product development process. *Journal of Engineering Design, 2,* 159-172.

Pallavicini, F., Argenton, L., Toniazzi, N., Aceti, L., & Mantovani, F. (2016). Virtual reality applications for stress management training in the military. *Aerospace Medicine and Human Performance, 87,* 1021–1030.

Park, J. L., Fairweather, M. M., & Donaldson, D. I. (2015). Making the case for mobile cognition: EEG and sports performance. *Neuroscience & Biobehavioral Reviews, 52,* 117-130.

Parr, J. V. V., Gallicchio, G., & Wood, G. (2021). EEG correlates of verbal and conscious processing of motor control in sport and human movement: a systematic review. *International Review of Sport and Exercise Psychology*.

Parsons, T. D., Gaggioli, A., & Riva, G. (2017). Virtual reality for research in social neuroscience. *Brain Sciences, 7*.

Porter, Jared Marak, "Systematically increasing contextual interference is beneficial for learning novel motor skills" (2008). *LSU Doctoral Dissertations*. 2980.

Proteau, L. (1992). On the specificity of learning and the role of visual information for movement control. In L. Proteau & D. Elliott (Eds.), *Vision and motor control* (pp. 67-103). North Holland.

Proteau, L., Martenuik, R., Levesque, L. (1992). A sensorimotor basis for motor learning: Evidence indicating specificity of practice. *The Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 44,* 557-575.

Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers & Education, 147*, 103778.

Rauter, G., Sigrist, R., Koch, C., Crivelli, F., van Raai, M., Riener, R., & Wolf, P. (2013). Transfer of complex skill learning from virtual to real rowing. *PLoS ONE, 8,* e82145.

Repperger, D. W., Gilkey, R. H., Green, R., LaFleur, T., & Haas, M. W. (2003). Effects of haptic feedback and turbulence on landing performance using an immersive cave automatic virtual environment (CAVE). *Perceptual and Motor Skills, 97,* 820-832.

Robert, M., Guberek, R., Levin, M., & Sveistrup, H. (2013). Motor learning of the upper limb in children with cerebral palsy after virtual and physical training intervention. *International Conference on Virtual Rehabilitation ICVR.* Valencia, Spain. pp. 194–195.

Rubin, M. (2021). When to adjust alpha during multiple testing: A consideration of disjunction, conjunction, and individual testing. *Synthese*.

Ryan, M. L. (2015). *2, Narrative as virtual reality 2: Revisiting immersion and interactivity in literature and electronic media (Vol. 2).* JHU Press.

Ryan, R.M. (1994). Intrinsic Motivation Inventory (IMI). http://selfdeterminationtheory.org/intrinsic-motivation-inventory/.

Salter, M., & Sanchez-Vives, M. V. (2016). Enhancing our lives with immersive virtual reality. *Frontier in Robotics and AI, 3,* 74.

Sandlund, M., Domellöf, E., Grip, H., Rönnqvist, L., & Häger, C.K. (2014). Training of goal directed arm movements with motion interactive video games in children with cerebral palsy - A kinematic evaluation. *Developmental Neurorehabilitation, 17,* 318–326.

Saunders, T., Driskell, J. E., Johnston, J. H., & Salas, E. (1996). The effect of stress inoculation training on anxiety and performance. *Journal of Occupational HealthPpsychology, 1,* 170-186.

Schmidt, D. A., Lange, C., & Young, D. E. (1990). Optimizing summary knowledge of results for skill learning. *Human Movement Science, 9,* 325-348.

Schmidt, R. A., Lee, T. D., Winstein, C., Wulf, G., Zelaznik, H. K. (2018). *Motor Control and Learning: A behavioral emphasis.* Human Kinetics.

Schmidt, R., & Lee, T.D. (1982). *Motor Control and Learning: A Behavioral Emphasis*.

Seymour, N. E., Gallagher, A. G., Roman, S. A., O'Brien, M. K., Bansal, V. K., Andersen, D. K., & Satava, R. M. (2002). Virtual reality training improves operating room performance: Results of a randomized, double-blinded study. *Annals in Surgery, 236,* 458–463.

Shea, C. H. & Kohl, R. M. (1990). Specificity and variability of practice. *Comparative Study, 61,* 169-177.

Sherman, W. R., & Craig, A. B. (2003). *Understanding virtual reality: Interface,aApplication, and design.* Morgan Kaufmann Publishers.

Singley, M. K., & Anderson, J. R. (1989). *The transfer of cognitive skill*. Harvard University Press.

Slater, M. (2009). Place illusion and plausibility can lead to realistic behavior in immersive virtual environments. *Philosophical Transactions of the Royal Society B, 364,* 3549-3557.

Slater, M., Pertaub, D., Barker, C., & Clark, D. M. (2006). An experimental study on fear of public speaking using a virtual environment. *Cyberpsychology & beahvior: the impact of the internet, multimedia, and virtual reality on behavior and society, 9,* 627-633.

Stansfield, S., Shawver, D., Sobel, A., & Prasad, M. (2000). Design and implementation of a virtual reality system and its application to training medical first responders. *Presence Teleoperators & Virtual Environment, 9,* 524-556.

Steuer, J. (1995). Defining virtual reality: Dimensions determining telepresence. In F. Biocca & M. R. Levy (Eds*.), Communication in the age of virtual reality* (pp. 33–56). Erlbaum.

Sutherland, I. (1968). A head-mounted three-dimensional display. Proceedings of the Fall Joint Computer Conference, pp. 757-764.

Szpak, A., Michalski, S. C., Saredakis, D., Chen, C. S., Loetscher, T. (2019). Beyond feeling sick: The visual and cognitive aftereffects of virtual reality. *IEEE Access, 7,* 130883-130892.

Thorndike E. L. (1914). *The psychology of learning*. Teachers College.

Tirp, J., Steingrover, C., Wattie, N., Baker, J., & Schorer, J. (2015). Virtual realities as optimal learning environments in sport-A transfer study of virtual and real dart throwing. *Psychological Test and Assessment Modeling, 57,* 57-69.

Todorov, E., Shadmehr, R., & Bizzi, E. (1997). Augmented feedback presented in a virtual environment accelerates learning of a difficult motor task. *Journal of Motor Behavior, 29,* 147-158.

Usoh, M., Catena, E., Arman, S., Slater, M. (2000). *Presence Teleoperators & Virtual Environments, 9.*

Vine, S. J., Moore, L., & Wilson, M. R. (2014). Quiet eye training: The acquisition, refinement and resilient performance of targeting skills. *European Journal of Sport Science, 14,* 235-242.

Walsh, K. R., & Pawlowski, S. D. (2002). Virtual reality: A technology in need of IS research. *Communications of the Association for Information Systems, 8,* 297-313.

Weiss, P.L., Keshner, E.A., & Levin, M.F. (2014). In P. Sharkey P (Ed.) *Applying virtualrReality technologies to motor rehabilitation: Virtual reality technologies for health and clinical Applications*. Vol. 1 Springer.

Whitwell, R. L., Ganel, T., Gyrne, C. M., & Coodale, M. A. (2015). Real-time vision, tactile cues, and visual form agnosia: Removing haptic feedback from a "natural" grasping task induces pantomime-like grasps. *Frontiers in Human Neuroscience, 9,* 216.

Wijeyaratnam, D. O., Chua, R., & Cressman, E. K. (2019). Going offline: Differences in the contributions of movement control processes when reaching in a typical versus novel environment. *Experimental Bran Research, 237,* 1431-1444.

Williams, A. M., Davids, K., & Williams, J. G. (1999). *Visual perception and action in sport*. Spon Press.

Witmer. B. G., & Singer, M. J. (1998). Measuring presence in virtual environments: A presence question. *Presence, 7* 225-240.

Wulf, G. & Lewthwaite, R. (2016). Optimizing performance through intrinsic motivation and attention for learning: The OPTIMAL theory of motor learning. *Psychonomic Bulletin & Review, 23,* 1383-1414.

Wulf, G. (2007). *Attention and motor skill learning.* Human Kinetics.

Wulf, G., & Shea, C. H. (2002). Principles derived from the study of simple skills do not generalize to complex skill learning. *Psychonomic Bulletin & Review, 9,* 185-221.

Vita

Logan Taylor Markwell grew up in Taylorville, Illinois where he played a variety of sports and was introduced to fitness. After graduating high school in 2013, he attended Southern Illinois University in Carbondale (SIU). During this time, he became a personal trainer and developed a strong interest in human movement. While he graduated with his bachelor's degree in criminal justice, he took a variety of kinesiology undergraduate courses as electives. It was during one of those classes where he was introduced to the field of motor behavior taught by Dr. Jared Porter. After realizing how many concepts from the field of motor behavior could be directly applied to his clients and athletes, he chose to pursue a master's degree in exercise science at SIU. Under the advisement of Dr. Philip Anton, he completed his thesis titled, *The Effects of Focus of Attention on Balance in Individuals who have Undergone Chemotherapy.* In 2023, he will receive his Doctor of Philosophy degree in Kinesiology and Sport Studies with a specialization in Sport Psychology and Motor Behavior. Logan is passionate about theory and practice, and the integration between the two.