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Intermanual Transfer of Motor Skills using Action Observation in a Virtual Reality Environment

by

Nancy Devine

A dissertation

submitted in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy in the Department of Psychology

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Committee Approval

To the Graduate Faculty:

The members of the committee appointed to examine the dissertation of Nancy Devine find it satisfactory and recommend that it be accepted.

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November 26, 2019

Nancy Devine and
James Ralphs
Physical Therapy
MS 8045

RE: Study Number IRB-FY2020-82 : Inter-manual transfer of motor skills using action observation in a virtual reality environment.

Dear Dr. Devine and Dr. Ralphs:

Thank you for your responses to a previous review of the study listed above. These responses are eligible for expedited review under OHRP (DHHS) and FDA guidelines. This is to confirm that I have approved your application.

Notify the HSC of any adverse events. Serious, unexpected adverse events must be reported in writing within 10 business days.

You may conduct your study as described in your application effective immediately. The study is subject to renewal on or before November 25, 2020, unless closed before that date.

Please note that any changes to the study as approved must be promptly reported and approved. Some changes may be approved by expedited review; others require full board review. Contact Tom Bailey (208-282-2179; email humsubj@isu.edu) if you have any questions or require further information.

Sincerely,

Ralph Baergen, PhD, MPH, CIP
Human Subjects Chair

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Dissertation Abstract—Idaho State University (2020)

Introduction: Intermanual transfer is seen following training of the dominant arm in a novel motor skill when it produces improvements in the untrained, non-dominant arm. Multiple modes of training, such as physical practice and action observation, have been found to induce intermanual transfer of motor skills. Virtual reality environments provide a novel means for investigating different forms of action observation during training and for assessing their influence on intermanual transfer. Previous research includes investigation of three different action observation conditions during training in a virtual reality environment on intermanual transfer using a non-purposeful finger sequence learning activity. The purpose of this study was to investigate the influence of three action observation conditions during training in a virtual reality environment on intermanual transfer of a goal-directed task.

Method: Participants (N = 24) were randomly assigned to three equal groups that received a counterbalanced sequence of the three action observation conditions during training of the dominant right hand to perform a virtual ball throwing task. The performance of the trained right arm and untrained left arm were tested during and after training as well as for retention.

Results: The trained right arm and the untrained left arm both improved during training and retained some skill in performing the novel virtual task. No differences were found between the three action observation conditions or the groups. No differences in performance were found due to gender, age, or the reported number of hours of daily video game play.

Discussion: Regardless of action observation condition, training in a virtual reality environment produced improvements in right arm performance and may have induced intermanual transfer in the untrained left arm. An alternative explanation may be that the random practice schedule of repeated testing of the untrained left arm influenced learning. Further research is needed to better understand the factors influencing motor learning in a virtual reality environment to identify potentially useful clinical applications.

Key Words: virtual reality, intermanual transfer, action observation, motor learning

Intermanual Transfer of Motor Skills using Action Observation in a Virtual Reality Environment

Overview

Through experience, humans and animals can adapt and change their motor behaviors to acquire and gain skill in performing new motor tasks (Norton & Wolpaw, 2018; Pierce & Cheyney, 2008; Shumway-Cook & Woolacott, 2007; Sullivan, Kantak, & Burtner, 2008). The extent and type of experience influences the rate of improved performance and the persistence of skilled ability. Direct training methods, such as physically performing the novel task, are an effective means for acquiring the initial ability, and developing skill, in performing a motor task (Norton & Wolpaw, 2018; Shumway-Cook & Woolacott, 2007). However, research also shows indirect training methods promote learning, often at a slower rate (Ossmy & Mukamel, 2016b; Taylor, Wojaczynski, & Ivry, 2011). During indirect training, no physical practice occurs by the extremity eventually tested for ability (Apšvalka, Cross, & Ramsey, 2018; Buchanan & Wright, 2011; Kai & Watari, 2005; Neva, Ma, Orsholits, Boisgontier, & Boyd, 2019). Examples of indirect training methods include action observation (Apšvalka et al., 2018; Buchanan & Wright, 2011) and inter-limb transfer (Kai & Watari, 2005; Neva et al., 2019). Indirect training may have clinical utility in rehabilitation when the extremity needed to perform a task is unable to participate in physical training due to injury, surgery, or lack of motor control following neurologic damage (Harmsen, Bussmann, Selles, Hurkmans, & Ribbers, 2015; Neva et al., 2019).

One form of indirect training, intermanual transfer, is achieved through physically training one hand to perform a task that aids performance gains in the untrained hand (Kai & Watari, 2005; Latash, 1999; Neva et al., 2019; Taylor et al., 2011). Although some studies investigating intermanual (or inter-limb) transfer were specifically interested in studying the processes of how learned motor strategies are represented, retained, and recalled (Boutin et al., 2012; Fu, Hasan, & Santello, 2011; Kai & Watari, 2005; Taylor et al., 2011), the findings of improved performance in the untrained arm/limb may have clinical utility when a limb is unable to engage directly in physical training.

Action observation, another form of indirect training, promotes acquisition and skill development in performing motor tasks (Apšvalka et al., 2018; Buchanan & Dean 2010; Farsi, Bahmanbegloo, & Abdoli, 2016; Hashimoto et al., 2015). Current methods of action observation training include passive observation while watching a video (Ansuini et al., 2016; Bozzacchi, Spinelli, Pitzalis, Guisti, & Di Russo, 2015; Nojima et al., 2012) or live demonstration (Simones et al., 2017), as well as the use of reflected active observation by using a framed mirror (or mirror box) (Nojima et al., 2012). The mirror provides an actively moving visual image of the inactive limb by reflecting the learner's other physically active limb (Nojima et al., 2012). Both forms of action observation (passive and reflected active) promote improved performance of the untrained limb (Ansuini et al., 2016; Apšvalka et al., 2018; Bozzacchi et al., 2015; Buchanan & Dean, 2010; Farsi et al., 2016; Hashimoto et al., 2015; Nojima et al., 2012; Simones et al., 2017).

During direct physical training, feedback influences the rate and extent of learning a novel motor task (Muratori, Lamberg, Quinn, & Duff, 2013; Ranganathan, Adewuyi, & Mussa-Ivaldi, 2013; Salmoni, Schmidt, & Walter, 1984; Shumway-Cook & Woollacott, 2007; Sullivan et al., 2008). Intrinsic feedback is the information available within the learner regarding the performance and outcome of each attempt at the task. Sensory input from muscle and joint receptors, tactile receptors, as well as auditory and visual sources, provide a rich array of information to inform the learner of what happened and, for purposeful tasks, whether the attempt was successful (Ostry, Darainy, Mattar, Wong, & Gribble, 2010; Shumway-Cook & Woollacott, 2007). Intrinsic feedback provides an important source of information for the learner to develop alternative motor strategies to acquire and develop skill in performing a novel task.

Virtual reality is a computer-programmed, artificial, three-dimensional environment that is typically displayed on a computer monitor or within a helmet or goggle mounted screen. Virtual reality environments may be used to interact with virtual objects, perform fictional or realistic virtual tasks, or compete in virtual games (Adamovich, Fluet, Tunik, & Merians, 2009). The essentially unlimited number of programmable virtual tasks provide a diverse and unique opportunity to implement direct and indirect training methods. In particular, programming the virtual reality environment to reflect the image of the user's arm (Ossmy & Mukamel, 2017b) provides a similar experience as reflected active action observation when using a mirror. However, the virtual reality environment is not limited to the size of the mirror and allows reflected active action observation training in a wider range and scope of uni-manual tasks. The virtual reality environment provides a means to manipulate the type of intrinsic feedback available to the learner.

The current study investigated the influence of different action observation conditions on intermanual transfer during, and after, learning of a novel virtual motor task. Participants trained the dominant arm using three action observation conditions. The performance of the non-dominant arm was tested before, during, and after dominant arm training. The three action observation conditions used during dominant arm training were passive action observation (PAO), active action observation (AAO), and reflected active action observation (RAO). Previous research by Ossmy and Mukamel (2017b) used these three action observation conditions to train participants' dominant hands in learning a virtual finger movement sequence.

They found the RAO condition produced the highest performance gains in the untrained, non-dominant hand. This study investigated the influence of the action observation conditions (PAO, AAO, and RAO) used by Ossmy and Mukamel (2017b) during training to perform a goal-directed virtual task instead of a non-purposeful finger movement sequence.

Motor Control and Motor Learning

Theories of Motor Control

Multiple theories and models of motor control have been proposed for describing how the sequence and timing of muscle contractions are controlled to produce motor behaviors such as posture, locomotion, and performing purposeful activities (i.e., drinking from a cup, driving a car etc.) (Bate, 1997; Guccione, Neville, & George, 2019; Muratori et al., 2013; Shumway-Cook & Woollacott, 2007). Historical models of motor control include the Reflex Model and the Hierarchical Model.

The Reflex Model of motor control describes movement as a series of reflexes elicited by sensory stimuli. Specific muscle contractions are the unit by which motor behaviors are controlled (Muratori et al., 2013; Shumway-Cook & Woollacott, 2007).

The Hierarchical Model states the central nervous system is organized from the top down with higher centers (motor cortex) controlling middle centers (subcortical structures and the brainstem) that control lower centers (spinal cord) of motor neurons. The unit of control by which motor behaviors are organized in the Hierarchical Model is at the level of movement patterns produced through the coordinated contraction of groups of muscles (Bate, 1997; Shumway-Cook & Woollacott, 2007).

Contemporary models of motor control have evolved from these earlier models and now often include a systems perspective in which the status of multiple systems in the body influence motor control for the specific task, within the context of the environment (Bate, 1997; Guccione et al., 2019; Muratori et al., 2013; Shumway-Cook & Woollacott, 2007). Currently, there is no universally accepted model of motor control (Shumway-Cook & Woollacott, 2007).

In my opinion, the most credible contemporary model of motor control is the Dynamic Systems Model. The Dynamic Systems Model of motor control (Systems Model) describes the control of movement as being organized based upon the task, the capabilities of the person performing the task, and the environment in which the task is being performed (Guccione et al., 2019; Shumway-Cook & Woollacott, 2007). The Systems Model proposes that the sequence and timing of muscle contractions emerges in a flexible, dynamic manner that self-organizes from the myriad number of attributes of the person, such as strength, range of motion, or endurance, the environment, such as stable, moving, or competing, and the task, such as single vs. two handed action, or variable vs. consistent action, to produce a movement strategy likely to be successful. Many options to perform the task are available and the specific sequence and timing of motor units contracting emerges based upon the interaction of the heterarchical body systems, within the current environment, to produce motor behaviors that meet the needs for the specific task requirements (Muratori et al., 2013).

An example of applying the Systems Model to describe the control of a person's motor behavior is to consider a person attempting to drink water from a vessel. Multiple movement strategies are available for the person to drink from a vessel. The type of vessel holding the water (glass, crushable paper cup, or water bottle with a cap etc.) will influence the grip and excursion of arm movement used by the person. If a person is right-hand dominant, and typically uses the right hand to drink from a glass, the person may organize the movement using the left hand instead if the right hand is occupied by holding a sleeping infant. If the person is holding an open container of water while standing up on a crowded, moving bus, the engagement of postural muscles, excursion of arm movements, and a heightened need to prevent spilling on adjacent passengers may further alter the movement strategies used. These scenarios provide brief examples of how an interaction between the person, environment, and task can influence the timing and sequence of muscle contractions ultimately observed as the motor actions used to achieve the task. The Systems Model provides an explanation for the tremendous variability available in motor behaviors that may be applied to perform the same task. It also provides an explanation for why some people with impaired motor control (i.e. following a stroke or head injury) may be unable to volitionally open the hand, but the hand may open when reaching for a cup of water while attempting to take a drink (Shumway-Cook & Woollacott, 2007). Motor behaviors may be elicited more easily when organized around a task with variable movement solutions, than when attempting to contract an isolated muscle, or muscle group, that produces no purposeful outcome.

Overview of Motor Learning

By definition, motor learning has occurred when there are observed changes in motor behavior that occur through experience with a task that 1) result in more frequent task success, 2) are retained at a later date following a period of no practice, and 3) may be transferred or generalized to other similar motor tasks (Magill, 2011; Muratori et al., 2013; Shumway-Cook & Woollacott, 2007). The motor control model employed influences the explanation of how motor learning occurs and may be facilitated (Guccione et al., 2019; Latash, 2010; Shumway-Cook & Woollacott, 2007). Applying the Systems Model, the selection of the task to be learned becomes important, as well as the structure of the environment in which it is learned, and the attributes of the learner (Guccione et al., 2019; Shumway-Cook & Woollacott, 2007). Although the attributes such as range of motion, strength, or endurance of the learner may be improved to aid motor learning, improving these attributes (e.g., increasing strength or endurance) becomes an ancillary activity while practice, through task training in the relevant environment, is emphasized. In addition, practice and feedback, can be structured to influence the rate of motor learning (Levin, Weiss, & Keshner, 2015; Muratori et al., 2013; Shumway-Cook & Woollacott, 2007). The Systems Model provides a framework in which the variable motor behaviors seen during training are explained as emerging through an interaction of multiple systems, for the specific task, within the specific environment and are influenced by experience.

Motor learning also may be explained as operant conditioning. The motor behaviors that emerge whose frequency of occurrence are influenced by the resulting consequences, are operant behaviors. Operant behaviors producing positive consequences, increase the frequency of that behavior in the future, while behaviors producing negative consequences decrease in frequency. In other words, the consequences of the operant behavior either increase (reinforcement) or decrease (punishment) the probability of the same behavior being repeated (Pierce & Cheyney, 2008; Thorndike, 1927). This capacity to change motor behaviors based upon experience underlies the ability to acquire and retain new motor behaviors (Pierce & Cheyney, 2008).

Consistent with the Systems Model, motor behavior occurs within an environmental context and, therefore, stimuli within the environment influence the occurrence of operant behaviors. A stimulus available just prior to performing the operant behavior that produced a positive consequence may become a discriminative stimulus that increases the probability the operant behavior will occur again in the presence of that stimulus in the future (Pierce & Cheney, 2008). Establishing discriminative stimuli that lead to an increased frequency of successful operant behaviors promotes the acquisition and retention of the ability to perform novel motor tasks following repeated trials, otherwise known as learning (Pierce & Cheney, 2008).

Learning to perform a novel motor task occurs in stages. There are multiple staging systems available, but most include an early stage of skill acquisition, and a later stage of skill refinement (Broderick & Newell, 1999, Latash, 2010; Shumway-Cook & Woollacott, 2007; Stöckel & Weigelt, 2012). During skill acquisition, the learner explores what the task requires and begins experimenting with different movement strategies to perform the task. Success may be infrequent and the movement strategies used are highly variable. Following practice and experience, further refinements in movement strategies produce a higher frequency of success at the task and more consistent strategies being used. Increasing skill is demonstrated by a reduction in the attention required to perform the task, the efficient use of momentum and passive body physics as part of the movement strategies, and the achievement of task success in a wide variety of environments and contexts (Broderick & Newell, 1999, Latash, 2010; Shumway-Cook & Woollacott, 2007; Stöckel & Weigelt, 2012).

In order to influence the rate of motor learning, training may purposefully structure the frequency and content of practice, the schedule and content of feedback, and the regulatory features of the environment. Organizing one or more of these components influences the rate of motor learning. The structure and amount of practice and the structure and content of feedback have the greatest influence on the rate of motor learning (Shumway-Cook & Woollacott, 2007).

Intrinsic and Extrinsic Feedback. Two sources of feedback include intrinsic (within the performer) and extrinsic (provided by an external source) feedback (Shumway-Cook & Woollacott, 2007). Extrinsic feedback, provided by an observer, may include knowledge of results (KR) or knowledge of performance (KP). Knowledge of results is a description of whether success was, or was not, achieved following one or more trials of the task. Knowledge of performance is a description of the movement strategies used during one or more trials of the task, and may include suggestions for specific alterations to try during future attempts (Shumway-Cook & Woollacott, 2007). Performers receive intrinsic feedback about the movement strategy used to attempt a task through one or more sensory systems including proprioception, tactile, visual, and auditory sources (Shumway-Cook & Woollacott, 2007). If the performer, using intrinsic feedback, can independently discern the outcome following an attempt at the task, it is termed response-produced feedback (Salmoni, 1984). Feedback during skill acquisition assists the performer to more rapidly understand the salient features and requirements of the task (Shumway-Cook & Woollacott, 2007). Although extrinsic KR is helpful, structuring trials and practice in a manner to enhance intrinsic response-produced feedback further improves the rate of motor learning (Salmoni et al., 1984).

Intermanual Transfer

Previous research has shown that training-induced motor skill in one limb also improves performance of the untrained contralateral limb (Boutin et al., 2012; Fu et al., 2011; Kai & Watari, 2005; Taylor et al., 2011), termed “intermanual transfer” for the upper limbs. In intermanual transfer, repeated training with one hand for the motor behaviors that increase success in task performance are then used by the untrained hand when performing the same task despite a lack of physical training experience (Fu et al., 2011; Kai & Watari, 2005; Taylor et al., 2011). Notably, the untrained arm and hand’s performance remains less skilled than the trained arm and hand (Fu et al., 2011; Kai & Watari, 2005; Taylor et al., 2011).

Kai and Watari (2005) investigated the influence of different KR feedback schedules on intermanual transfer of learning a grip force control task. They divided participants into 10 different KR schedules ranging from none to following every attempt at the task. Only the dominant hand received physical training through performing 30 trials of the grip force task. Both hands were subsequently tested for performance of the grip force task following the initial training session, one day later, and one week later. They found that both hands successfully performed the novel grip task with some differences in skill level seen across KR schedules. The outcomes indicated intermanual transfer occurred during task acquisition and retention since the non-dominant hand performed just slightly less well than the trained dominant hand across the KR schedules at each testing session.

Latash (1999) investigated intermanual transfer of reflected writing. Participants trained by writing with the dominant hand to produce a written phrase that looked correct within a mirror, rather than on the page. Training sessions consisted of writing the phrase, while watching the mirror, five times in a row, three times each day, for five consecutive days. The total length of time required to write the phrase five times and the total number of illegible letters both served as the measure of skill level. The skill level of both the participants' hands were tested before training, after training, and by using a novel phrase with the same number of letters after training. Intermanual transfer was inferred for the reflected writing task as demonstrated by the skill level of the untrained non-dominant hand, although poorer, being approximately parallel to the skill level of the dominant hand across testing sessions.

The results of intermanual transfer studies indicate the changes in motor behavior occurring during training with one hand will influence the motor behaviors of the untrained hand, but at a lower level, of novel task performance. The factors, such as speed, timing, influence of gravity, or momentum, influencing success or failure to perform the task, rather than the movement patterns used, appear to be the most salient features of what is transferred when testing the untrained hand. Although studies of intermanual transfer provide information about how motor skills are learned and represented within the central nervous system, they may also have clinical relevance as a means for providing intervention to maintain or improve hand and arm function when one arm is unable to participate in direct physical training.

Action Observation

Action observation, or observational practice, is a form of indirect training in which learning and skill development occurs through watching the performance of the task (Buchanan & Wright, 2011; Farsi et al., 2016). Despite the absence of physical training, a measurable improvement in performance occurs through training administered by watching a video (Apšvalka et al., 2018; Breslin, Hodges, & Williams, 2009; Iacoboni & Mazziotta, 2007), watching a live performer (Buchanan & Dean, 2010; Buchanan & Wright, 2011), actively using one's own arm while watching the reflected image in a mirror (Harmsen et al., 2015), or within virtual reality (Farsi et al., 2016; Ossmy & Mukamel, 2016b; Ossmy & Mukamel, 2017b; Ossmy & Mukamel, 2018). In order for the indirect training effect to occur, previous research indicates the actions being observed need to be realistic, such as using a life-like hand image rather than a simplistic line drawing, and be a real task instead of just a posture or non-purposeful limb movement (Breslin et al., 2009; Farsi et al., 2016; Iacoboni & Mazziotta, 2007; Rizzolatti & Luppino, 2001; Stefan et al., 2005).

Action observation is proposed to improve performance by indirect training through activation of the "mirror neuron system" in the brain (Rizzolatti & Luppino, 2001). The mirror neuron system is composed of groups of neurons that display activation during observation of a task that is almost equivalent in intensity to the activation observed during actual performance of the task (Iacoboni & Mazziotta, 2007). The groups of mirror neurons are distributed throughout different parts of the brain and respond to different observed inputs (Pineda, 2008). For example, mirror neurons located in the anterior intraparietal region are active when observing a task that requires visual input to guide the grasping motions of the hand. The mirror neurons in the inferotemporal cortex are active when observing a task in which the object being manipulated by the hands, such as a pen during writing, must be understood and differentiated from a pencil (Pineda, 2008).

The connections made by the mirror neuron system with the somatosensory and motor cortices provide a means by which observation may produce an internal representation of how to perform the observed task (Breslin et al., 2009; Pineda, 2008). The observer's implicit understanding of the purpose or intent of the movement strategies seen while watching task performance have a stronger influence on mirror neuron activation than the observation of the movements used. The internal representation, or the neurologic connections between mirror neurons in the somatosensory and motor cortices, has been found to display neuroplasticity and learning through training with action observation (Breslin et al., 2009; Ossmy & Mukamel, 2018; Pineda, 2008). Action observation provides a means of indirect training that follows similar principles as motor learning through direct physical training, and whose foundation for learning lies within central nervous system changes.

Farsi et al. (2016) compared direct physical training, two forms of action observation using video and kinematic figure displays, and a control group on participants' learning of the three phases of a sprinter's crouch (ready, set, go). All participants received a pre-test of their initial ability, trained for four blocks of 20 trials per day for the next two days and received a post-test on the following (4th) day of the study. At the post-test, the physical training group performed the best, followed by the video action observation group, followed closely by the kinematic figure display group, in comparison to the control group. These results suggest that physical training provides the greatest gains for learning a complex movement combination required for sprinting competitions, but gains still can be made through indirect training using different forms of action observation.

Buchanan and Dean (2010) studied the influence of action observation of a live model performing a timed, bimanual contrived task. The participants were paired as model and observer, and then distributed into two groups. One group of pairs received explicit instructions on the strategy to use to complete the contrived task successfully and the observer watched the model implement the instructions. The model in the other group of pairs used discovery learning to seek potential movement strategies to succeed at the task while the observer watched. All participants received a pre-test, a post-test following training, and a retention test 24 hours later. All of the models performed 30 practice trials per day for two days between the pre-test and the post-test while the observers watched. They found that the observers in the explicit instruction group specifically used the same movement strategies to complete the contrived task as their paired models and performed more successfully for this contrived task. The observers of the models using discovery learning used highly variable movement strategies, rather than duplicating the strategies used by their models. Neither the models, nor the observers, of the discovery learning group performed as well as the explicit verbal instruction group. These results indicate that action observation is influenced by the verbal instructions that guide the learner toward the likely movement solution. Discovery learning still produced action observation learning in the observer, but the observer appears to learn to attempt multiple strategies rather than discovering the model's successful strategy among the multiple trials and attempts at the task. What is challenging to interpret in these findings is the influence the use of a contrived task had on action observation, versus a purposeful task that may be used in daily life.

Nojima et al. (2012) studied two forms of action observation. In the first experiment, participants placed both hands in a box. The box for one group contained a mirror that provided visual feedback as if both hands were present and independent, but the left hand was a mirrored reflection of the right hand. The box for the other group had glass so both real hands were visible. For both groups, the left hand remained passive during training of the right hand in a palm ball rotation task. During post-training testing, the untrained left hand in the mirrored box group demonstrated greater improvements in skill than the standard box group. In the second experiment, the mirror-box group procedures remained the same, while the standard box now contained a digital monitor on which a video of a passive right hand and the left hand performing the palm ball rotation task. Both hands of the video box group remained at rest during training with the video. During post-testing, the left hand improved in both the active action observation group (mirror) and the passive action observation group (video). These findings suggest that the use of a mirror to provide a reflected image provides a means for action observation and provides an additional method for indirect training.

Harmsen et al. (2015) investigated the use of mirror action observation as an addition to physical training for people with reduced arm function due to chronic hemiplegia following a stroke. A pre-test measured the time and acceleration of each arm while reaching from the side of the body to a target directly in front of the participant. Participants were randomly assigned to either a mirrored action observation group or a control group. The mirrored action observation group recorded and subsequently viewed a video of a reflected mirror image of the intact arm performing a reaching movement. The control group viewed a video containing a series of still landscape images. Participants in both groups alternated training by viewing the videos from 1 – 3 minutes and performing 20 -30 trials of a reach-to-target movement with the involved arm in a fixed and equivalent sequence. A post-test repeated the measures of time and acceleration of the involved arm while reaching to the target. The results showed both groups reduced the time required to reach to the target and increased arm acceleration during the reach. In addition, the mirrored action observation group was faster, with greater arm accelerations, than the control group. These findings indicate that adding a mirrored action observation component to a reaching intervention augmented the physical training outcomes for people with reduced motor control of the arm after a stroke.

Ossmy and Mukamel (2017b) investigated the influence of different methods of action observation on intermanual transfer of learning a finger movement sequence. In the first experiment, they compared passive action observation (PAO), active action observation (AAO), and reflected active action observation (RAO) conditions. The PAO group watched a video of a virtual left hand performing the finger movement sequence while keeping their hands at rest on their laps. The AAO group viewed a virtual right hand image, controlled by their own right hand, as they physically trained by performing the finger movement sequence. The RAO group viewed a virtual left hand image, controlled by a reflected image of their own right hand, as they physically trained by performing the finger movement sequence. The pre-test and post-test consisted of the number of correct finger movement sequences performed by the left hand. All groups showed improvement, with the RAO group showing the most improvement overall. These results indicate that multiple forms of action observation are effective for learning a finger movement sequence by the untrained, non-dominant hand. In addition, the two forms of indirect training, action observation and intermanual transfer, may be used together. Lastly, the reflected image of actively using the dominant hand within the RAO group provided the greatest influence on learning outcomes.

The results of these studies of action observation indicate the changes in motor behavior occurring during training influences the motor behaviors of the untrained hand, even in a clinical sample. Although the evidence regarding how mirror neurons are activated indicates the benefits of using a task rather than an arbitrary movement pattern during action observation training, the current research demonstrates effective outcomes with movement patterns and with tasks. Action observation may provide a powerful means for providing indirect training to arms and hands unable to participate in direct training methods.

Virtual Reality

A virtual reality (VR) environment provides a unique setting and context to manipulate and study motor learning (Adamovich, 2009; Balienson et al., 2008; Levin et al., 2015). VR has been defined as a "...user-computer interface that involves real-time simulation of an environment, scenario or activity that allows for user interaction via multiple sensory channels" (Adamovich et al., 2009, p. 29). While portions of the virtual, animated world will appear similar to the real world, the programming and technical capacities of the computer systems inherently provide a delay in the processing of visual content. In addition, some forces such as the presence of gravity, may be altered within the VR environment. Virtual systems that provide an avatar (a virtual representation of the user) provide visual feedback that the user must learn how to control in order to interact and successfully navigate the virtual world (Adamovich et al., 2009).

One advantage of using VR for research is that it can be programmed to meet the needs of the study (Adamovich et al., 2009). For instance, programming can provide the reflected image of the user's arm, instead of using a framed mirror in the real world (Ossmy & Mukamel, 2017b). The use of VR to generate a reflected image provides an advantage over using a framed mirror by increasing the arm's allowable area of excursion, since it is no longer limited by a frame or the size of the mirror. It also provides an almost unlimited number of tasks that can be programmed (Adamovich et al., 2009), particularly tasks that cannot be accomplished in front of a mirror, such as ball throwing, or juggling in which the environment required for the task is larger than what the reflected image of a framed mirror reflecting the active arm can accommodate.

Multiple aspects of using VR to study motor learning have been investigated, including how head-mounted VR goggles influence visuomotor adaptation (Anglin, Sugiyama, & Liew, 2017), perceptual learning in virtual environments (Albert et al., 2005; Kim, Kretch, Zhou, & Finley, 2018; Morice, Siegler, Bardy, & Warren, 2007; Welch & Sampanes, 2008), feedback while learning in VR (Balienson et al., 2008; Eaves, Breslin, van Schaik, Robinson, & Spears, 2011; Rao et al., 2018), comparisons of learning in VR versus the real world (Bezerra et al., 2018), improvements in skill compared to brain activity in an electroencephalogram (Calabrò et al., 2017), processes during motor skill acquisition (Ludolph, Giese, & Ilg, 2017), and neuroplasticity associated with VR learning (Prochnow et al., 2013). In particular, VR is an engaging, effective environment that can be manipulated to enhance feedback and motor learning while adjusting to the user's interests and abilities (Adamovich et al., 2009).

The VR environment provides an ideal means for studying the influence of different forms of action observation feedback on motor learning and intermanual transfer since the environment, task, and forms of action observation can be manipulated and the outcomes assessed. Ossmy & Mukamel (2017b) used a VR environment to test the influence of three different forms of action observation on the intermanual transfer of learning a specific sequence of finger movements. Although the RAO condition produced the greatest outcomes in the non-trained hand's performance of the sequence of finger movements, it is still unknown how learning a novel motor task under different action observation conditions influences intermanual transfer and retention of a purposeful, goal-directed, task within a virtual environment.

Current Study

The purpose of the current study was to examine the influence of three action observation feedback conditions on the intermanual transfer of performance. Specifically, the effects of training the dominant arm in a virtual ball-throwing task on motor skill performance of the untrained, non-dominant arm engaging in the same task was investigated. The visual feedback provided during task practice occurred through a VR environment and was manipulated experimentally to provide PAO, AAO, and RAO conditions. Previous investigation of intermanual transfer of motor skill through the use of VR action observation conditions used a non-purposeful sequence of finger movements (Ossmy & Mukamel, 2017b), not a goal-directed motor task. This study investigated intermanual transfer of a goal-directed task using VR to provide different action observation conditions during motor skill training.

Research Questions and Hypotheses

The following three research questions and hypotheses were posed for this study:

Question 1: Does the non-dominant arm display a change in performance during dominant arm training sessions employing a virtual motor skill, 24-48 hours after dominant arm training, and are any observable changes equivalent to changes in the dominant arm's performance?

Q1 Hypotheses:

Q1 H_0: There is no significant change in non-dominant arm performance:

$H_{01.1}$: during dominant arm training employing a virtual motor skill (Post-test score = Pre-test score).

$H_{01.2}$: 24 – 48 hours after dominant arm training (Retention test score = Pre-test score).

$H_{01.3}$: when compared to change in dominant arm performance . ($R_{\text{Post-test score – Pre-test score}} = L_{\text{Post-test score – Pre-test score}}$; $R_{\text{Retention test score – Pre-test score}} = L_{\text{Retention-test score – pre-test score}}$; $R_{\text{Retention test score – Post-test score}} = L_{\text{Retention-test score – post-test score}}$)

Q1 H_1: There is a significant change in non-dominant arm performance following dominant arm training (Post-test score – Pre-test score > 0).

Q1 H_2: There is a significant change in non-dominant arm performance 24 – 48 hours after training (Retention test score – Pre-test score > 0).

Q1 H_3: The change in performance of the dominant arm is significantly different than the change in the non-dominant arm. ($R_{\text{Post-test score – Pre-test score}} \neq L_{\text{Post-test score – Pre-test score}}$; $R_{\text{Retention test score – Pre-test score}} \neq L_{\text{Retention-test score – pre-test score}}$; $R_{\text{Retention test score – Post-test score}} \neq L_{\text{Retention-test score – post-test score}}$)

Question 2: Do different visual feedback conditions for action observation influence inter-manual transfer during dominant arm training sessions employing a virtual motor skill?

Q2 Hypotheses:

Q2 H_0: There is no significant difference in non-dominant arm performance between any of the three action observation conditions during dominant arm training. (Non-dominant arm performance PAO = AAO = RAO)

Q2 H_1: Non-dominant arm performance will differ based upon the action observation training condition the dominant arm experienced during training. (PAO ≠ AAO ≠ RAO)

Question 3: Does the dominant arm display a change in performance following dominant arm training sessions employing a virtual motor skill and/or 24-48 hours after dominant arm training?

Q3 Hypotheses:

Q3 H_0: There is no significant change in dominant arm performance:

$H_{01.1}$: following dominant arm training employing a virtual motor skill.

($R_{\text{Post-test score}} = R_{\text{Pre-test score}}$)

$H_{01.2}$: 24 – 48 hours after dominant arm training. ($R_{\text{Post-test score}} = R_{\text{Pre-test score}}$; $R_{\text{Post-test score}} = R_{\text{Retention score}}$).

Q3 H_1: There is a significant change in dominant arm performance directly following training. ($R_{\text{Post-test score}} \neq R_{\text{Pre-test score}}$)

Q3 H_2: There is a significant change in dominant arm performance 24 – 48 hours after training ($R_{\text{Post-test score}} - R_{\text{Pre-test score}} \neq R_{\text{Post-test score}} - R_{\text{Retention score}}$).

Most of the procedures used in Experiment 1 from Ossmy & Mukamel (2017b) were replicated with some modifications. The primary modification was training the participants to perform a goal-directed virtual ball-throwing task in place of the non-purposeful virtual finger movement sequence (Ossmy & Mukamel, 2017b). In order to confirm the dominant arm displayed a training effect, this study added testing of the participants' dominant arm in addition to testing the non-dominant arm for intermanual transfer effects. A retention test for both arms was also added in order to assess whether any changes in performance following training persisted.

Method

Participants

Right-handed adults between the ages of 18 – 35 years, who have no reported neurological, visual, or perceptual deficits and report having fully functioning arms and hands bilaterally were recruited for this study. Participants needed to report having no previous experience using VR goggle gaming systems and be willing to attend two study sessions. All participants received $10.00 for their participation ($5.00 for Session 1 and $5.00 for Session 2) and some students received course credit if they enrolled in the study through the SONA Research Management System.

The study by Ossmy & Mukamel (2017b) found significant differences between conditions using a sample size of 18 participants. A larger number of participants (N = 24) was recruited for this study in order to allow for any potential differences in detecting changes in the performance of a non-purposeful finger movement sequence vs. a goal-directed motor task.

Experimental Design

A repeated measures, randomized counterbalanced design was used in which all participants experienced all three feedback conditions with equal numbers experiencing them in one of three sequences (Table 1).

Table 1

Counterbalanced Participant Allocation

	Feedback Conditions		
Participant Allocation	Passive Action Observation	Active Action Observation	Reflected Active Action Observation
n = 8	1	2	3
n = 8	2	3	1
n = 8	3	1	2

Equipment and Virtual Tasks

Virtual Reality Device

The VR device consisted of a commercially available Oculus Rift (Oculus, Menlo Park, CA) VR headset fitted and integrated with a LEAP Motion Controller (LEAP Motion, San Francisco, CA) (Figure 1). Programming of the virtual tasks and environments used in this study were developed using Unity 3D software (Unity Technologies, San Francisco, CA).

The VR device fitted over the participants' eyes in the form of opaque goggles mounted on a headset that positions internal screen lenses in front of the eyes (Figure 1B) and speakers over the ears. The position of the screen lenses was adjustable from narrow to wide to accommodate different facial widths. An adjustable frame and straps allowed the participant to customize the fit to the size of the head, counterbalance the weight of the goggles in front, and to maintain a consistent seal with the face (Figure 2). When donned, the VR device restricted the visual field to seeing only what was contained on the internal screen lenses within the goggles with a black surround. Cords exited the back of the headset and connected the VR device to an Alienware 15 laptop gaming computer (Dell, Round Rock, TX) (Figure 3A). The laptop display provided an image of what the participants' viewed within the VR goggles (Figure 3B). Due to the LEAP motion integration with the Oculus Rift, the participant could see a replica of his/her own arm when it was placed within the sensor field in front of the VR device. The animated replica consisted of a forearm, wrist, and articulated hand. As the participant moved the arm within the sensor field, the animated replica displayed a nearly equivalent movement of the forearm, wrist, hand, and fingers in space and time. The arm image within the VR device disappeared if the participant's arm moved out of the sensor field. When the arm returned to the sensor field, the arm image appeared in a different color with up to four different colors available (blue, green, red, and yellow). Errors occasionally occured in the accuracy of the arm/hand movements being conveyed within the VR device in which the participants' movements were either not registered or were inconsistent with the movements of the arm/hand image (estimated to be < 5% of attempts).

Figure 1. Virtual reality device from the front/side view (A) and the bottom/internal view (B)

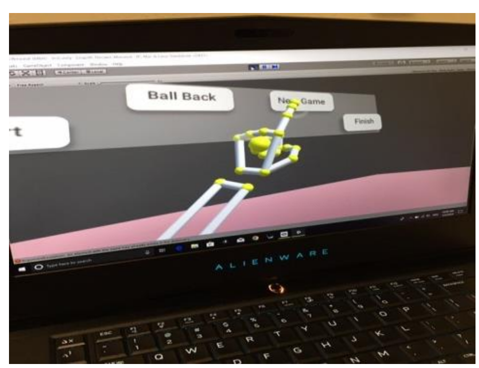
A. Oculus Rift with mounted LEAP

B. Bottom and inside view of Oculus Rift

Figure 2. User wearing the virtual reality device

Figure 3. Virtual reality device with the computer.

A. Virtual reality device, sensor and computer.



B. User's view conveyed on laptop screen.

Virtual Reality Tasks

The VR tasks used in this study included stacking blocks and throwing a ball at a target. Both tasks required the participant to reach up to press virtual buttons to gain access to additional blocks or balls (Figure 3B). A successful button-push by the virtual hand provided visual feedback through the sudden appearance of a new virtual block or ball, as well as auditory feedback by hearing a “click” when the button was virtually depressed far enough by the hand image. Grasping the virtual ball or block with the virtual hand image required the hand to be located over the object in the virtual environment and then making a grasping movement. The ends of the fingers of the virtual hand actually disappear into the object as if they are grasping the very center rather than the surface. Releasing the object required opening of the hand and at times, the virtual object appeared to stick to the fingers. The programmed VR environment of the two tasks does not accurately reflect the effects of gravity so the object does not easily roll or fall out of the hand when opened.

The virtual block-stacking task provided opportunities to retrieve multiple blocks (no limit in number) by pushing the button and then grasping and moving the blocks into a stack on top of each other or throwing them through the virtual environment. Blocks may be batted with the back of the hand and will deflect when hit by another block.

The virtual ball-throwing task provided the opportunity to retrieve one ball at a time, pick it up, and throw it at a target of six stacked blocks arranged in a pyramid (three on the bottom, two in the middle, one on top). The ball can miss, nudge, or knock down the blocks when thrown. When the ball is no longer within reach, such as after a throw, the participant may press the virtual “New Ball” button to obtain a new ball to make another attempt. When the participant is successful in knocking down the stacked blocks, the participant may push the “New Game” button to receive a new ball and a new target of stacked blocks.

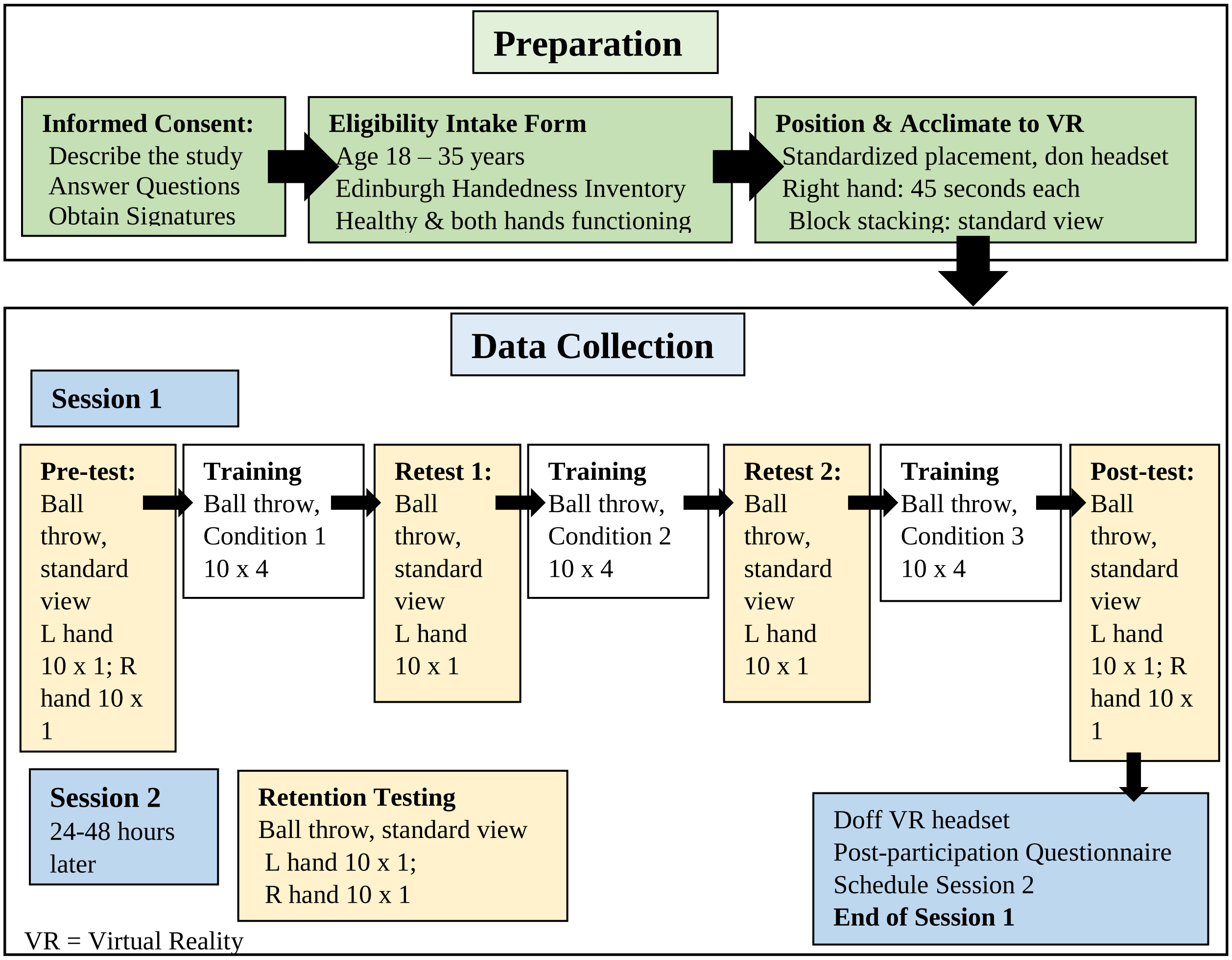
Two different versions of both the block-stacking and ball-throwing tasks were programmed. The standard version of the virtual tasks provides a virtual image of the same hand being used by the participant, whereas the reflected version provides a virtual image of the opposite hand being used by the participant. To clarify, in the standard view, the user sees a virtual image of the right hand when using the right hand. In the reflected view, the user sees a virtual image of the left hand when using the right hand. This study used both the standard and reflected views of the block-stacking task briefly to acclimate participants to the virtual environment and used both the standard and the reflected versions of the ball-throwing task for data collection.

Procedures

Consent and Eligibility to Participate

People interested in participating in the study were verbally informed about the study and provided with an opportunity to ask questions about the requirements. A written informed consent form was given to those who choose to continue and they were asked to read and sign the document (Figure 4). After obtaining consent, participants were assigned an anonymous code that randomly allocated them to one of three groups that varied only by the sequence of exposure to the three VR feedback conditions (Table 1). An Excel random number generator was used to randomize the assignment via the anonymous codes.

Figure 4. Summary of Procedures



All participants completed an intake form (Appendix A) to identify inclusion criteria (age 18 – 35 years, right handed [Edinburgh Handedness Inventory – Short Form; Veale, 2014; Appendix B]), exclusion criteria (reduced function in one arm/hand, history of neurologic injury, cannot sit for $\geq$ 40 minutes, VR gaming experience), and gender (Figure 4). The intake form also included questions regarding attributes that could influence motor learning in a VR environment such as previous ball throwing experience and an estimate of the amount of time spent playing video games daily.

Participant Positioning and Fitting of the VR Device

Participants were seated in a chair (seat 49 cm. from the floor) without armrests in a standardized location and distance from the VR sensor (82 cm. chin to sensor). The VR sensor was located on a table (76 cm. from the floor) in front of them and the angle of the VR sensor's inferior to superior position was adjusted to match each participant's height. The participant was oriented to the adjustments available on the VR device headset and then assisted to don the device and maximize comfort (Figure 4).

Acclimation to the Virtual Reality Environment

Once the participant was comfortable with the fit of the VR device, then he/she was acclimated to the VR environment using the block-stacking task beginning with the standard view. All participants received the same standardized instructions during the acclimation period to guide them through learning the extent of the virtual sensor field, how to manipulate the virtual forearm, wrist, and fingers, how to manipulate the virtual buttons to retrieve five blocks. Once five blocks were obtained, the participant was given 45 seconds to practice picking up the blocks, stacking them, and/or throwing them with the right hand. The same procedures were then followed with the reflected view of the block stacking task using the right arm. After 45 seconds elapsed, the participant was asked to stop and therefore ending the acclimation to the virtual environment portion of the study (Figure 4).

Pre-Test

Following acclimation to the VR environment and prior to training, the standard view of the VR ball-throwing task was opened and participants were briefly oriented to the virtual "New Ball" button that provides a new ball and the virtual "New Game" button that provides a new ball and a new target of stacked blocks.

Participants were then tested on their initial ability to throw the virtual ball to hit the target in the standard view (Figure 4; Session 1: Pre-test). Participants received standardized instructions (Appendix C) to perform one set of 10 throws, first with their left arm and then with their right arm. Participants were informed they had a limit of 1.5 minutes to complete the set of 10 throws for each arm. During the Pre-test, participants were verbally cued when there were two remaining throws in each set of 10, when each set of 10 throws was complete, and if the 1.5 minutes expired. The result of each throwing attempt (hitting or missing the target) was documented in an Excel spreadsheet immediately following each throw.

Training Conditions

After the Pre-test data were collected, the participants began training the right arm in the virtual ball-throwing task under the first of the three different feedback conditions (PAO, AAO, or RAO) based upon the randomized assignment indicated in Table 1 (Figure 4).

Passive Action Observation Condition. During training in the PAO condition, participants were passive observers of the motor task being performed. Participants were seated 3.5' from a laptop computer that played a digital video of a virtual left hand performing the virtual ball-throwing task. Participants received standardized instructions to attend to the digital video and to maintain both of their hands at rest on their thighs throughout the duration of the video. The video showed four trials (10 attempts/trial) of the virtual left hand performing the task with a 10-second break between each trial. No virtual reality headset was used during this condition.

Active Action Observation Condition. During training in the AAO condition, participants actively used the right hand while observing the virtual right hand perform the task. Participants were seated in the same standardized position used during acclimation to the VR environment and the Pre-test while wearing the VR headset. The standard view of the virtual ball-throwing task was used and participants received standardized instructions to use the right hand to manipulate the virtual right hand on the screen to perform four trials (10 attempts/trial) of throwing the ball with the goal of hitting the target as many times as possible. A 10-second break was provided between each trial and the participants were required to perform each trial within 1.5 minutes.

Reflected Active Action Observation Condition. During training in the RAO condition, participants actively used the right hand while observing the virtual left hand perform the task. Participants were seated in the same standardized position used during acclimation to the VR environment and the Pre-test while wearing the VR headset. The reflected view of the virtual ball-throwing task was opened and participants received standardized instructions to use the right hand to manipulate the virtual left hand on the screen to perform four trials (10 attempts/trial) of throwing the ball with the goal of hitting the target as many times as possible. A 10-second break was provided between each trial and the participants were required to perform each trial within 1.5 minutes.

Retests 1 and 2

Following completion of right arm training under each of the first two VR conditions, a retest of the left arm’s ability was conducted (Retest 1 and Retest 2; Figure 4). During the retest, participants were seated in the same standardized position used during the Pre-test while wearing the VR headset. A script was used to provide standardized instructions requesting the participant to perform one set of 10 throws at the target with the left arm in the standard view within 1.5 minutes. The participant was encouraged to hit the target as many times as possible during the 10 throws. Each participant was verbally cued when there were two remaining throws in the set of 10, when the set of 10 throws was complete, and if the 1.5 minutes expired. The result of each throwing attempt (hitting or missing the target) was documented in an Excel spreadsheet immediately following each throw.

Post-test and Retention Testing

Following completion of training under the third VR condition, a Post-test was administered (Figure 4; Session 1: Post-test). During Session 2, 24 – 48 hours after completing Session 1, a Retention test was administered (Figure 4; Session 2: Retention Testing). During the Post-test and the Retention test, participants were seated in the same standardized position used during the Pre-test while wearing the VR headset. The same procedures used for the Pre-test (i.e. testing the performance of the left and right hands) were repeated yielding documentation of the number of hits/misses for each set of 10 throws with the left and the right arms.

End of Sessions

At the completion of Sessions 1 and 2, the headset was removed and cleaned using cleansing wipes. The participant was instructed to remain seated for one minute in order to adjust to the real world instead of the virtual world. Participants then completed a Post-participation Questionnaire (Appendix D) indicating their experiences during the first session and estimating their future performance during Session 2 (Figure 4).

Following completion of Session 1, the participants were reminded to return for Session 2 at a date and time within 24 – 48 hours. The participants were given $5.00 for participating in each session and asked to sign a receipt book. For the participants eligible for SONA credit, I logged into the SONA system after each session and reported attendance. All paper data collected were stored in a 3-ringed binder in a filing cabinet while digital data were saved to a laptop computer and to a secure cloud storage file in Box.

Reliability Testing

In order to calculate reliability of the scoring method used during this study, four participants' Pre-test performances were digitally recorded for later viewing and scoring. The digital recordings were stored on the laptop computer and in a secure cloud storage file in Box.

Data Analysis

Data were organized within Excel spreadsheets and imported into Stata 16.0 statistical software (StataCorp, LLC, College Station, Texas) for data analyses using a significance level of 5%. Descriptive statistics, such as frequencies of the demographic characteristics of the sample (age, gender, daily videogame playing) were calculated, as well as the sums, means, and SEMs for the scores achieved during each testing time (Pre-test, Retests 1 and 2, Post-test, and Retention test) and by condition (PAO, AAO, and RAO).

In order to detect differences between different action observation feedback conditions on the intermanual transfer of right-hand training to left- hand performance, the data analysis used by Ossmy & Mukamel (2017b) was applied by calculating a performance gain index (G index). The G index was calculated using the formula:

$$G = \frac{\text{Post-test} - \text{Pre-test}}{\text{Post-test} + \text{Pretest}}$$

The G index was calculated for each participant using the Pre-test, Retest 1, Retest 2, and Post-test to reflect left arm performance changes after each right arm VR training condition (PAO, AAO, RAO), as well as to reflect the overall performance change at the Retention test (from Pre-test and from Post-test). In addition, a G index was also calculated for each participant using the Pre-test, Post-test and Retention test to assess right arm performance changes. A positive G index indicated a performance improvement while a negative G index indicated a decline in performance. Since participants experienced the three feedback conditions in different sequences, the G indexes were calculated by using the testing value of the training condition experienced just prior to the Retest or Post-test (POA, AAO, or RAO). Dependent t-tests were used to compare the left arm G indices of the POA and AAO feedback conditions, POA and RAO feedback conditions, and the AAO and RAO feedback conditions (Research Question 2).

In order to determine if motor learning occurred during training (Session 1), dependent t-tests were used to compare the mean of the Pre-test scores to the mean of the Post-test 3 scores for the left and the right hands. Dependent t-tests were used to compare the mean of the Pre-test scores to the means of the Retention test scores for the left and right hands to determine if any change in performance was retained (Session 2) following a gap in practicing the task (Research Question 1). The independent variables were either the observation feedback condition (POA, AAO, and RAO) or group (sequence of conditions experienced). The dependent variables were the mean number of successful throws at the target. A Bonferroni's correction was used to set the level of significance to $p = 0.017$ for conducting three comparisons.

A repeated measures ANOVA was used to assess the influence of the independent variables of gender, age, or daily videogame playing on the dependent variable of the scores achieved.

Results

Participants

A total of 25 people participated in this study with 24 contributing data to the analyses. The removal of one participant's data was required due to inconsistencies in performance impacted by the wearing and removal of a large hair elastic around the right wrist during data collection. The participants ranged in age from 18 – 34 years, were all right hand dominant as measured by the Edinburgh Handedness Inventory, and reported no previous experience using virtual reality goggles. All but one of the participants were randomly assigned to the sequence of conditions experienced (Groups A, B, or C) with equal numbers (n = 8) for each group. One participant was assigned to the same condition sequence as the participant whose data were removed. The descriptive characteristics of the participants by group, and as a whole, are listed in Table 2.

Table 2

Participant Characteristics

Group	Gender		Age (years)			Ball Throwing History		Daily Video Game Play	
	Female	Male	Mean	SD	Median	Average	Advanced	0-1 hour	2-3 hours
A	4	4	21.4	2.7	20.0	8	0	7	1
B	3	5	22.6	4.5	21.0	4	4	7	1
C	6	2	25.1	5.6	24.5	6	2	7	1
Total	13	11	23.5	4.7	20.5	18	6	21	3

Groups A and B were more similar in the distribution of men and women (Group A = 50% each; Group B 62% men, 38% women) and were closer in age while Group C was older and had more women (75%) than men (25%). One quarter of the sample reported having advanced ball throwing experience through participation in baseball (n = 3), softball (n = 2), or regularly throwing balls for a pet dog (n = 1). The majority of the sample (88%) reported playing video games less than one hour per day.

Combined Outcomes

Collectively, the participants completed a total of 1,200 attempts to hit the target with their untrained left arms (5 testing sessions, 10 throws/test, 24 participants) yielding 872 hits (73%, M = 36.3, SD = 5.5). Using their right arm, the participants each completed 120 training throws (4 sets of 10 throws, in each of 3 VR conditions) and collectively, completed 720 attempts to hit the target (3 testing sessions, 10 throws/set, 24 participants) yielding 553 hits (77%, M = 23.0, SD = 4.6).

Overall Performance of the Untrained Left Arm

A Shapiro Wilk Test indicated the data were normally distributed for the Pre-test, Post-test, and Retention test scores for the left arm. Dependent t-tests indicated the left arm Post-test scores (M = 7.29, SD = 2.26) were higher than the Pre-test scores (M = 5.79, SD = 2.11), $t(23) = 2.49$, $p = 0.02$. A dependent t-test also indicated Retention test scores (M = 8.29, SD = 1.4) were higher than the Pre-test scores (M = 5.79, SD = 2.11), $t(23) = 6.83$, $p < 0.001$, but there was no significant difference in the Retention test scores and the Post-test scores, $t(23) = 1.92$, $p = 0.07$. These results indicate the number of successful left arm throws increased following right arm training and the improvement was retained 24 – 48 hours later (Figure 5).

Overall Performance of the Trained Right Arm

The Shapiro Wilk Test indicated the data for the right arm were normally distributed for the Pre-test and Post-test scores but the Retention test scores ($z = 1.97$, $p = 0.02$) were positively skewed (M = 7.96, SD = 2.14; Median = 9). Dependent t-tests indicated the right arm Post-test scores (M = 8.33, SD = 1.63) where higher than the Pre-test scores (M = 6.58, SD = 2.59), $t(23) = 3.21$, $p = .004$. A Wilcoxon signed-rank test indicated the right arm Retention test score was higher than the Pre-test scores, $Z = 4.9$, $p < 0.001$, but the Retention test score was lower than the

Post-test score, Z = -4.27, $p < 0.01$. These results indicate the number of successful right arm throws increased following training but the improvement in motor behavior was not fully retained 24 – 48 hours later (Figure 5).

Figure 5. Performance of the left and right arms

Note: The mean number of throws that hit the target made by the trained right arm and the untrained left arm at the initial Pre-test, the Post-test which occurred after training in all three VR conditions, and 24-48 hours later at the Retention test. Bars show SEM. * = significant difference between the Left and Right arms; ♦ = significant difference from Pre-test score; ● = significant difference from Post-test score. 2-tailed significance $p < 0.05$)

Comparisons of the Trained Right and Untrained, Left Arm Performance

T-tests indicated there were no differences between the Pre-test scores of the left and right arms, t(23) = 1.24, $p = 0.23$, but the right arm Post-test scores were higher than the left arm scores, t(23) = 2.13, $p = 0.04$. A Wilcoxon signed-rank test indicated the Retention test scores of the left arm were higher than the right arm scores, Z = 4.23, $p < 0.001$. These results indicate the right arm performed better than the left arm during training, but the left arm retained the virtual throwing ability while the right arm's ability declined from the post-test to the retention test (Figure 5).

Comparison of the changes in success for the untrained left arm and the trained right arm from the Post-test to the Retention test were done using calculation of the G index. A dependent t-test (2-tailed) indicated there was a significant difference in performance gain between the left and right arms t(23) = 2.13, $p = 0.04$. The performance gain of the left arm was greater than the performance gain in the right arm.

A 2-way repeated measures ANOVA comparing the effects of arm (left or right) and testing session (Pre-test, Post-test, or Retention) on the participants' score indicated there was no main effect for arm, F(1) = 1.44, $p = 0.24$. The test showed a main effect of testing session F(2) = 12.27, $p < 0.001$ with the Post-test scores and Retention test scores being higher than the Pre-test scores for both arms. There was no significant interaction between arm and test session F(2)=2.00, $p = 0.14$.

Virtual Reality Condition Training Effects on Left Arm Performance

Performance Gains by Virtual Reality Condition

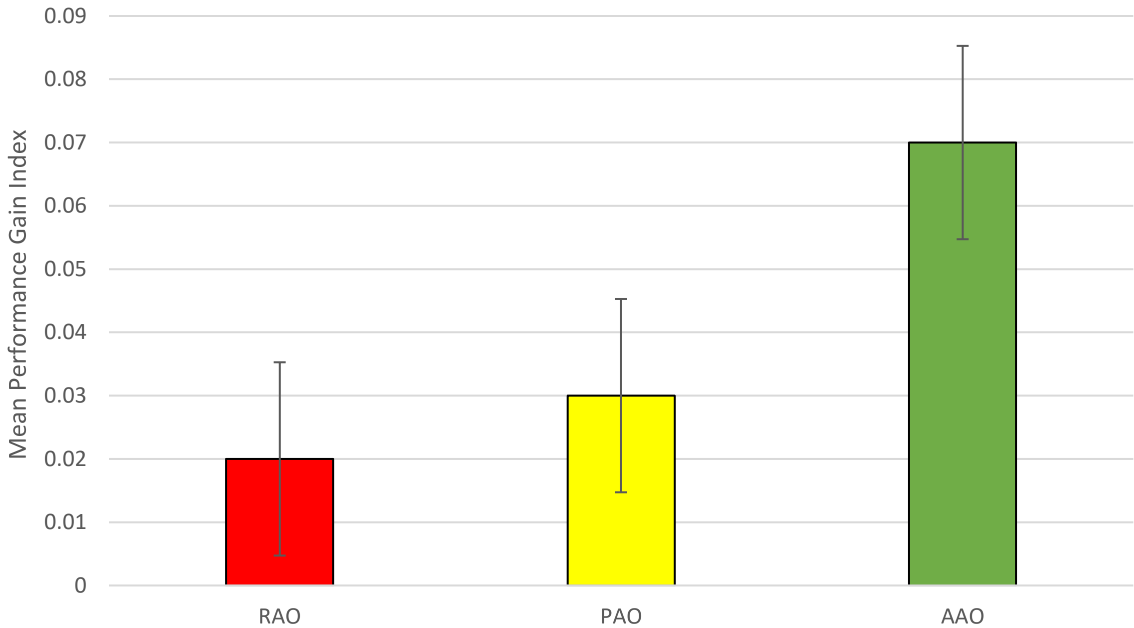
Applying the data analyses approach used by Ossmy & Mukamel (2017b), performance gain indices (G index) for each participant were calculated following training in each virtual reality condition and the overall mean G index was calculated for each condition (Table 3; Figure 6). A Shapiro Wilk Test indicated the G indices for the RAO condition, Z = -0.549, p = 0.7, and the AAO condition, Z = -1.365, $p = 0.91$, were normally distributed while the G indices for the PAO condition, Z = 3.23, $p = 0.001$, were positively skewed (M = 0.03, SD = 0.17; Median = 0.00).

A 2-tailed paired t-test revealed no difference between the left arms' performance gains following the RAO (M = 0.02, SD = 0.19) and AAO (M = 0.07, SD = 0.21) VR training conditions [t(23) = -0.82, $p = 0.42$]. A Wilcoxon signed-ranks test revealed no significant differences in the performance between the PAO (M = 0.03, SD = 0.17) and AAO (M = 0.07, SD = 0.21), VR training conditions (Z = -0.87, $p = 0.38$) or the PAO (M = 0.03, SD = 0.17), and RAO (M = 0.02, SD = 0.19) VR training conditions (Z = -0.11, $p = 0.91$). These results indicate the VR training condition did not influence left arm performance during, or after, right arm training.

Left Arm Performance by Sequence of Virtual Reality Conditions Experienced (Groups)

A Shapiro Wilk Test revealed the left arm Pre-test, Post-test, and Retention-test scores were normally distributed for Groups A, B, and C. The group summary statistics for the left arm (Table 4) and group performance for both arms across all testing sessions (Figure 7) are provided. A repeated measures ANOVA was conducted to compare the effects of virtual reality condition sequence (Group) on the Pre-test, Post-test, and Retention test scores. A significant main effect was found for testing session [$F(2,21) = 12.5$, $p < 0.001$] (Retention test > Post-test > Pre-test) but no significant effect was found for Group [$F(2,21) = 0.50$, $p = 0.613$] or for the interaction of testing session by Group [$F(2,21) = 1.12$, $p = 0.358$]. These results indicate the different sequences of VR training conditions experienced by the three groups did not influence the throwing success of the left arm.

Figure 6. Mean G index by virtual reality condition



Note: Histogram of the mean performance index (G index) by virtual reality. RAO = Reflected Action Observation, PAO = Passive Action Observation, AAO = Active Action Observation. Bars are SEM.

Table 3

Participant Left Arm Performance Gain Index by Virtual Reality Condition

	Reflected Action Observation			Passive Action Observation			Active Action Observation		
ID	Pre-test	Post-test	G Index	Pre-test	Post-test	G Index	Pre-test	Post-test	G Index
1	9	5	-0.29	8	8	0	8	9	0.06
2	3	7	0.40	7	9	0.13	9	8	-0.06
3	3	7	0.40	7	8	0.07	8	10	0.11
4	8	9	0.06	9	7	-0.13	8	8	0.00
5	9	10	0.05	10	9	-0.05	7	9	0.13
6	9	10	0.05	10	10	0.00	4	9	0.38
7	9	8	-0.06	5	6	0.09	6	9	0.20
8	4	6	0.20	7	6	-0.08	6	4	-0.20
9	6	8	0.14	8	7	-0.07	7	10	0.18
10	5	7	0.17	7	3	-0.40	7	5	-0.17
11	10	9	-0.05	6	6	0.00	6	10	0.25
12	6	7	0.08	7	9	0.13	6	6	0.00
13	9	10	0.05	10	10	0.00	10	9	-0.05
14	8	7	-0.07	7	7	0.00	7	8	0.07
15	7	9	0.13	9	9	0.00	9	6	-0.20
16	7	7	0.00	6	7	0.08	7	7	0.00
17	6	7	0.08	7	6	-0.08	2	6	0.50
18	3	2	-0.20	5	6	0.09	6	3	-0.33
19	10	6	-0.25	6	8	0.14	4	10	0.43
20	9	8	-0.06	8	9	0.06	9	7	-0.13
22	8	7	-0.07	7	6	-0.08	4	8	0.33
23	7	9	0.13	9	10	0.05	10	10	0.00
24	4	2	-0.33	2	9	0.64	9	7	-0.13
25	6	4	-0.20	3	4	0.14	4	6	0.20

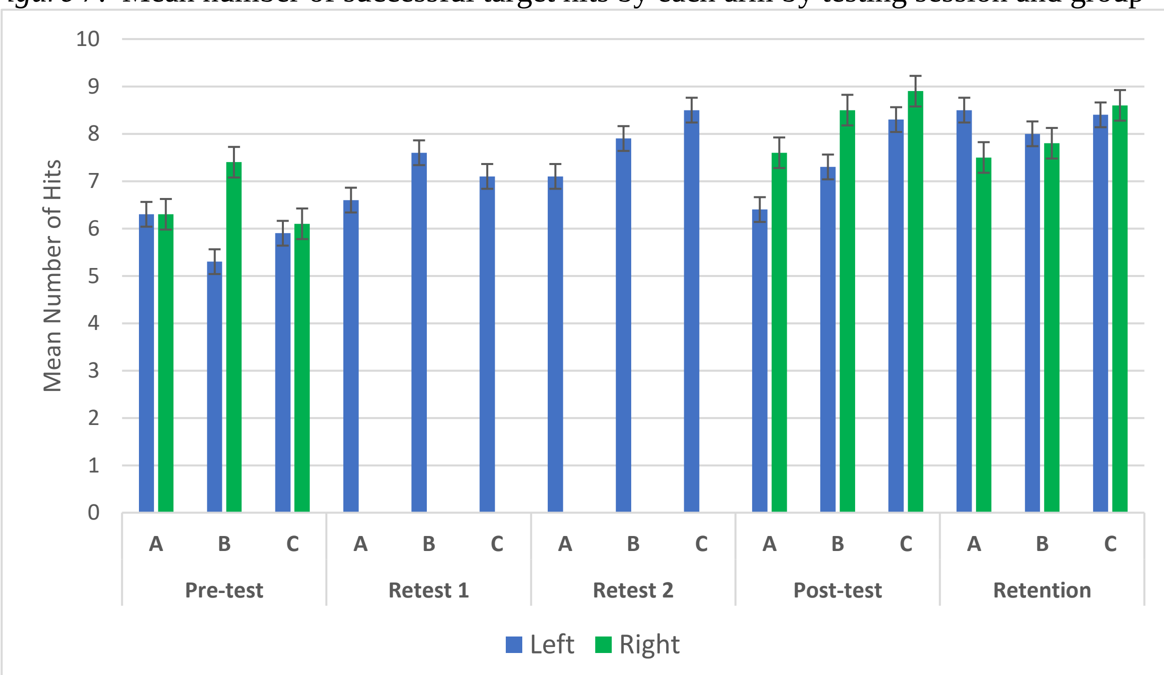
Table 4

Group Means (SD) by Arm and Testing Session

Group (Condition Sequence)	A (n = 8) (PAO, AAO, RAO)		B (n = 8) (AAO, RAO, PAO)		C (n = 8) (RAO, PAO, AAO)	
Test Session / Hand	Left	Right	Left	Right	Left	Right
Pre-test	6.3 (2.1)	6.3 (2.6)	5.3 (2.1)	7.4 (1.7)	5.9 (2.3)	6.1 (3.4)
Retest #1	6.6 (1.8)		7.6 (1.8)		7.1 (2.2)	
Retest #2	7.1 (2.6)		7.9 (1.6)		8.5 (1.1)	
Post-test	6.4 (2.7)	7.6 (2.0)	7.3 (2.3)	8.5 (1.3)	8.3 (1.6)	8.9 (1.5)
Retention Test	8.5 (1.5)	7.5 (2.5)	8.0 (1.5)	7.8 (2.4)	8.4 (1.3)	8.6 (1.5)

SD = standard deviation; Group A = passive action observation, active action observation, reflected action observation; Group B = active action observation, reflected action observation, passive action observation; Group C = reflected action observation, passive action observation, active action observation. Left = left arm, Right = right arm.

Figure 7. Mean number of successful target hits by each arm by testing session and group



Note: This histogram compares the left and right arms' performance by group across each testing session. Only the untrained left arm was tested during the Retest 1 & 2 sessions following training in the first two active observation conditions. There were no significant differences in left arm performance by group. Bars are SEM. (A = PAO, AAO, RAO; B = AAO, RAO, PAO; C = RAO, PAO, AAO)

Influence of Participant Characteristics on Performance

A repeated measures ANOVA compared the effects of gender on left arm Pre-test, Post-test, and Retention test scores. The main effect of test session was significant [$F(1,22) = 12.70$, $p = 0.0000$] (Retention test > Post-test > Pre-test) while the main effect of gender was not significant [$F(1,22) = 1.88$, $p = 0.184$].

A repeated measures ANOVA compared the effects of age on left arm Pre-test, Post-test, and Retention test scores. The main effect of test session was significant [$F(3,20) = 7.30$, $p = 0.0020$] (Retention test > Post-test > Pre-test) while the main effect of age was not significant [$F(2,21) = 0.65$, $p = 0.594$].

A repeated measures ANOVA compared the effects of the number of reported hours of daily video game playing on left arm Pre-test, Post-test, and Retention test scores. The main effect of test session was significant [$F(1,22) = 8.44$, $p = 0.0008$] (Retention test > Post-test > Pre-test) while the main effect of daily video game playing was not significant [$F(1,22) = 2.08$, $p = 0.164$]. Taken together, these results indicate gender, age, and daily video game play did not influence left arm throwing success.

Effect Size

The effect size of comparing the G-indices for the normally distributed RAO and AAO VR conditions was calculated to be $d = 0.25$ using the pooled standard deviation (Coe, 2002). No effect size was estimated for comparisons of the G-indices with the PAO condition because the data were not normally distributed.

The effect sizes of comparing the means of the Group Post-test scores ranged from $d = 3.59$ (Group B to Group A) to $d = 8.56$ (Group C to Group B) were fairly robust using a pooled standard deviation (Coe, 2002).

Reliability of Scoring

Reliability testing of the live scoring performed during data collection was conducted by re-scoring four participants' performance during the Pre-test during viewing of digital recordings of the session. A Kappa test indicated 100% agreement between the live scoring and the video scoring for all four participants, Z = 15.49, $p < 0.001$.

Intra-rater reliability was assessed by having two trained investigators observe and score the same four recorded videos of Pre-test sessions. A Kappa test indicated 100% agreement between the two trained investigators and the live scoring, Z = 8.94, $p < 0.001$.

Discussion

The results of this study demonstrate that performance improvements using a novel motor task can occur in the untrained non-dominant arm following training of the dominant arm in a virtual reality environment. The action observation conditions used, or the sequence in which they were experienced, during dominant arm training did not influence the changes in motor performance of the untrained non-dominant arm. Although both arms began with equivalent abilities in performance of the novel motor skill, as expected, the trained dominant arm performed better than the untrained non-dominant arm at the end of training. Interestingly, the trained dominant arm's abilities then declined between the end of training and follow-up retention testing 24 – 48 hours later, while the untrained non-dominant arm's abilities were retained, providing the only testing session in which the left arm scores were higher than the right arm scores. No influence of age, gender, or the reported daily amount of time spent playing video games on performance of the right or left arms were found.

Changes in Performance of the Non-Dominant Arm (Research Question 1)

The scores achieved by the non-dominant (left) arm from Pre-test to Post-test and to the Retention test significantly increased indicating intermanual transfer of the novel motor skill of throwing a virtual ball at a target occurred through training the dominant (right) arm. Intermanual transfer has also been found to occur following training in non-purposeful tasks such as modulating grip force (Kai & Watari, 2005), rapidly moving the fingers in a specific sequence (Ossmy & Mukamel, 2017b), and arm reaching movements to match a pattern (Boutin et al., 2012) or to reach a target (Neva et al., 2019). The pattern of greater improvements being achieved by the trained right arm than the untrained left arm during training seen in this study is consistent with previous research (Boutin et al., 2012; Kai & Watari, 2005, Neva et al.,2019; Ossmy & Mukamel, 2017b). This study further contributes to the evidence that training the right arm in a motor skill improves left arm performance of that skill.

One difference between the findings reported here and those in previous studies (Boutin et al., 2012; Kai & Watari, 2005; Neva et al., 2019) was that the participants' left arm Retention scores were higher than the right arm Retention scores. I found no other published study in which the untrained arm's performance was better than the trained arm. Typically, motor performance improves during training, in the trained and untrained arms, but retention tests consistently show a slight degradation in ability when a gap in training occurs, even over a 24 – 48 hour period (Boutin et al., 2012; Kai & Watari, 2005; Magill, 2011; Neva et al., 2019; Shumway-Cook & Woolacott, 2007). One potential explanation for the lack of degradation seen in the Retention scores of the untrained left arm achieved in this study may be that the left arm received a total of five testing sessions (Pre-test, Retest 1, Retest 2, Post-test, Retention test) that provided a total of 50 attempts (10 throws for 5 tests) at the task. The repeated testing may have served as a form of random practice, which has been shown to improve retention during direct training for motor skills (Magill, 2011; Shae & Morgan, 1979). Each participant completed a total of 150 virtual throws with the right arm during training (40 throws x 3 conditions) and testing (10 throws x 3 tests) which may have served as a form of blocked practice. Blocked practice has been shown to improve performance but impair retention (Magill, 2011). If so, then the differences in scores between the left and right arms may also reflect the influence of blocked vs. random practice schedules rather than a sole effect of intermanual transfer. Further research is needed to distinguish whether increases in performance are due to intermanual transfer or the effects of practice schedule on learning and retention of motor skills by the nondominant arm.

Influence of Action Observation Conditions on Performance (Research Question 2)

No difference in scores for the left arm were found by calculating performance gains following each of the visual feedback action observation training conditions (PAO, AAO, or RAO) or by the sequence in which the training conditions were experienced (Group A, B, or C). This differs from the study conducted by Ossmy & Mukamel (2017b) which found the RAO condition produced the greatest improvements in the untrained left hand in performing a specific finger sequence movement following virtual training of the right hand. The most notable differences between the Ossmy & Mukamel (2017b) study and the present study were the activities used for motor learning (non-purposeful movement sequence vs. task), the measures of success (timed vs. set trials) and the number of left hand/arm repeated tests conducted. Any one or more of these in combination could have influenced the outcomes achieved.

The use of a non-purposeful finger movement sequence requires learning greater specificity of movement action since there is only one finger movement sequence that produces success. In contrast, the purposeful task of throwing a ball to hit a target requires the use of a larger number of joints (shoulder, elbow, wrist, and hand) and therefore a larger number of muscle groups. The ball throwing task may be accomplished successfully using a myriad number of diverse movement strategies. The task allows, and may even promote, developing variable,complex movement strategies while the finger movement sequence requires the specific timing and activation of a smaller number of joints and muscle groups. Some evidence indicates the differing demands of an activity alter the brain processes that occur during learning and are directly influenced by complexity (Shae et al., 2011). Activity complexity delays performance gains and increases variability in the strategies used (Shae et al., 2011). The complexity of using a purposeful task may make comparisons to studies using less complex, non-purposeful, movement sequence challenging. Further research is needed to investigate the influence of activity complexity on the outcomes of learning through different action observation conditions.

The measure of motor learning success used in the current study differed from that used in Ossmy and Mukamel (2017b), primarily due to the activity used for learning and testing. Ossmy and Mukamel (2017b) measured success by the number of correct finger sequence movements completed in 30 seconds, which capitalizes on the opportunity to detect a speed vs. accuracy tradeoff during motor learning. This study used the total number of throws that hit the target out of 10 attempts as the measure of success which emphasizes precision and skill over speed. This disparity between measures of success may have contributed to the lack of consistent findings between the two studies despite applying an otherwise similar methodology and data analysis.

Since all participants in the current study and the Ossmy and Mukamel (2017b) study were trained under all three action observation visual feedback conditions (PAO, AAO, and RAO), they were divided into three counterbalanced groups so that all conditions were experienced first, second, or third by 1/3rd (n = 8) of the sample. The Ossmy and Mukamel (2017b) study conducted a left hand Pre-test and a Post-test before and after every visual feedback condition used during right hand training. In the current study, the Retest or Post-test score from the previous visual feedback condition was used as the Pre-test score for the next visual feedback condition in order to reduce the number of times participants performed the task to purposefully diminish a potential training effect for the left arm. The three additional left hand tests the participants in the Ossmy and Mukamel (2017b) study received during right hand training could be one source for the differences in the findings of the current study. Future research could use a larger sample size in which each group only receives one of the action observation conditions to test the influence on left arm learning following right arm training. This strategy would reduce the number of tests the left arm performs while providing a more definitive investigation of the impact of each action observation condition on intermanual transfer.

Other than the Ossmy and Mukamel (2017b) study, no other studies investigating multiple forms of action observation visual feedback conditions on motor learning were found in the literature. Some studies investigated differences in the content of action observation, such as observing a partial-body or the whole body of a cricket bowler (Breslin et al., 2009) and observing a video or a point-light model representation of a sprinter’s start (Farsi et al., 2016) but there is a dearth of literature investigating manipulations of action observation visual feedback conditions within a single study.

Changes in Performance of the Dominant Arm (Research Question 3)

The trained right arm’s Post-test and Retention test scores were significantly higher than the Pre-test scores indicating changes in motor skill occurred during training that were retained 24 – 48 hours later. It is notable, and not unusual, that the right arm’s Post-test scores were higher than the Retention test scores. Following a gap in the opportunity to practice, motor skills commonly decline a bit (Magill, 2011; Shumway-Cook & Woollacott, 2007). The results of this study confirmed the right arm displayed motor learning through training by including a Post-test and Retention test for the trained right arm. Since the trained right arm and the untrained left arm both displayed motor learning, it is possible to suggest the dominant arm training induced the changes in the motor skills of the untrained, non-dominant arm through intermanual transfer. Many (Boutin et al., 2012; Kai & Watari, 2005; Neva et al., 2019; Taylor et al., 2011), but not all, studies investigating intermanual transfer test the abilities of the trained arm during the study (Ossmy & Mukamel, 2017b). The Ossmy and Mukamel (2017b) study inferred intermanual transfer occurred without confirming the trained right hand’s ability following training. Testing the trained arm, in addition to the untrained arm, for changes in ability following training provides evidence to support the suggestion that intermanual transfer occurred. Future research investigating intermanual transfer should include measures of the trained arm/hand to strenghten any conclusions made that intermanual transfer was the source for improvements achieved by the untrained arm/hand.

Influence of Participant Characteristics on the Outcomes Achieved

Despite recruiting participants through a sample of convenience, an almost equal number of males and females joined the study (M = 11, F = 13). However, the outcomes indicated there were no differences in virtual task performance gains based upon gender, age, or the reported number of hours spent playing video games daily. The lack of a gender effect could be consistent with previous findings that the gender gap previously seen in technology use is dissipating (Choi et al., 2012; Kitson et al., 2016). The lack of findings may also be due to myriad other factors. Future research that purposefully controls for the effects of gender, age, and digital gaming experiences could provide a more robust investigation regarding whether these participant characteristics influence motor learning performance in a VR environment.

Potential Implications for Motor Learning

This study investigated motor learning using a novel task in a virtual reality environment. Since motor learning is influenced by the task, feedback, environment, and practice schedule (Magill, 2011, Shumway-Cook & Woollacott, 2007), other manipulations of these components could produce different learning outcomes. The virtual ball throwing task fits the criteria for a discrete task that has a definitive beginning (pick up the ball and aim) and ending (ball thrown with a trajectory that either hit or missed the target). The classification of the task used (discrete, serial, or continuous) could influence the outcomes of motor learning studies.

The level of difficulty or challenge of the task may also influence outcomes. Although the left arm Pre-test scores ranged from 2 – 10 hits (M = 5.79, SD = 2.11), one of the 24 participants achieved a perfect score (10/10). Following right arm training, five participants achieved a perfect score. This could indicate the novel task was too easy and may also be an indicator of the stage of the learner. Finding a means for assessing the difficulty or challenge level of a novel task, or the stage of the learner for that task, may be warranted prior to using the task in a study of motor learning.

A blocked practice schedule was used during training of the right arm in this study and the outcomes achieved were consistent with previous research indicating blocked practice facilitates improved performance of a discrete task during the training session but leads to greater loss of skill when tested during retention (Magill, 2011). However, no studies have examined the influence of blocked or random practice schedules on intermanual transfer.

The environment may be purposefully structured to influence motor learning. The virtual environment used in this study was not altered or manipulated as part of the study. The programmed environment required the participants to discover through experience how to perform successfully in the novel virtual world. The virtual environment provides a unique means for studying motor skill acquisition since it requires discovery learning for how to succeed in controlling the virtual arm. Previous experiences with virtual reality, real-world ball throwing, or athletics are unlikely to aid the user due to the novel programming of the environment for each virtual task. Future studies could develop tasks in which the virtual environment is manipulated to better understand factors influencing motor learning.

The different action observation conditions used in this study provided the participants with different intrinsic feedback when performing the task. The PAO condition provided visual feedback only, since both arms were at rest. The video used for the PAO condition provided a means for viewing different strategies for performing the ball throwing task the participant may not have used. Any misses or successes may have been less reinforcing since the participant had not actually performed the throw and had no direct engagement in the outcome. The AAO condition provided response-induced intrinsic feedback (Salmoni, 1984) that is directly related to the participant's attempt at the task. During the AAO and RAO conditions, a miss was likely to provide response-induced feedback that the most recently used strategy was unsuccessful and therefore reduce the likelihood of repeating that particular strategy in the future. Conversely, a throw that hit the target may have provided a form of reward that would act as reinforcement to increase the likelihood of the strategy being used again. However, no means for directly measuring the participants' perceptions of the outcomes of each throw were made in this study. It is unclear how each participant's attention to the task, the perception of what produced a hit or a miss, or motivation to perform may have influenced the outcomes achieved in this study. Future studies could incorporate more direct measures to assess how attention, perceptual processes, and motivation influence the interpretation of response-induced intrinsic feedback and motor learning.

Limitations

This study used a sample of convenience recruited from a single community in one state. The inclusion criteria restricted participants to certain ages and hand dominance. Any findings from this study may not be generalized to other age groups or to those who are left handed or ambidextrous. The VR goggle set was developed by Mechanical Engineering faculty and students at Idaho State University, and therefore the programming of tasks is likely to be unique. A large number of participants were recruited using the SONA system and their motivation to participate to obtain course credit may have influenced the effort and interest they displayed during the study. There were likely aspects of motor learning within this study that were not controlled, measured or identified.

Future Research

This study provided further evidence that a virtual reality environment may be used to manipulate the components of motor learning and to produce intermanual transfer of motor skills. Participants' improved their Post-test and Retention scores regardless of action observation condition or group, in the trained dominant arm as well as the untrained, non-dominant arm. Further research is needed to investigate the influences of the virtual activity (movement pattern or task) and whether the visual feedback conditions used alters learning of simplistic vs. complex movement patterns or tasks. For example, future research could include kinematic measures of changes in movement patterns used as changes in performance improve

during learning in a VR environment. Investigating whether participants are discovering a consistent set of movement patterns across participants to succeed in a novel motor task, versus finding a variety of individual movement solutions that all yield success at the task, would provide more information about motor learning and motor control. Such findings could influence how to best apply clinical interventions that rely on action observation for intermanual transfer of learning a motor skill.

Future research could also address the most effective mode of delivery of VR training. This study used a virtual reality goggle system, but it is currently unknown if interacting with other VR delivery systems (Wii, Kinect, or augmented reality systems) produce different outcomes. As technology continues to improve, as processing speeds become even more rapid, it is likely that VR technology may provide an even greater number of opportunities to manipulate and investigate motor learning. Discovering the ideal parameters and components for task-specific VR motor learning has the potential to provide a unique mechanism for aiding rehabilitation interventions, athletic accomplishments, and any trade or profession that requires skilled motor abilities.

Future research also could investigate the participant characteristics that influence VR motor learning. Discovering the attributes, experiences, and capabilities that influence VR motor learning could yield opportunities to adapt VR training to the specific needs of the learner. Ideally this research could be ongoing, as VR devices are becoming more common for entertainment and employment situations.

Lastly, this study did not identify the response-induced visual stimuli that were most salient during training that resulted in changes in motor behavior that became more effective with increased practice. Future research investigating the role of perception, and its influence on motor learning in a VR environment would provide more information that could influence the programming of virtual tasks to make the critical elements influencing success or failure more readily detectable.

Conclusion

Training of the dominant right arm in a novel VR task under three different action observation conditions resulted in improved performance in both arms. The scores for the right arm were higher than the left arm scores for the Post-test, but the scores for the Retention test 24-48 hours later were higher for the left arm than the right arm. Neither the action observation condition nor the sequence of experiencing the action observation conditions influenced motor performance. No influence of gender, age, or reported daily videogame playing duration was found on motor performance. Taken together, the results of this study suggest virtual reality tasks may be used to improve motor skills in the trained and untrained arms and may be implemented using either a video of someone performing the task, actively using the extremity to virtually perform the task, or actively using one extremity to control a reflected image of the other extremity to virtually perform the task.

References

Adamovich, S. V., Fluet, G. G., Tunik, E., & Merians, A. S. (2009). Sensorimotor training in virtual reality: a review. *NeuroRehabilitation*, *25*, 29-44.

Albert, G., Renaud, P., Chartier, S., Renaud, L., Sauvé, L., & Bouchard, S. (2005). Scene perception, gaze behavior, and perceptual learning in virtual environments. *CyberPshcyology & Behavior, 8*, 592-600.

Anglin, J. M., Sugiyama, T., & Liew, S.-L. (2017). Visuomotor adaptation in head-mounted virtual reality versus conventional training. *Scientific Reports*, *7*, 45469. doi: 10.1038/srep45469

Ansuini, C., Cavallo, A., Koul, A., D'Ausillo, A., Taverna, L., & Becchio, C. (2016). Grasping others' movements: rapid discrimination of object size from observed hand movements. *Journal of Experimental Psychology: Human Perception and Performance*, *42*, 918-929.

Apšvalka, D., Cross, E. S., & Ramsey, R. (2018). Observing action sequences elicits sequence-specific neural representations in frontoparietal brain regions. *The Journal of Neuroscience*, *38*, 10114-10128.

Bailenson, J., Patel, K., Nielsen, A., Bajscy, R., Jung, S-H., & Kurillo, G. (2008). The effect of interactivity on learning physical actions in virtual reality. *Media Psychology*, *11*, 354-376.

Bate, P. (1997). Motor control theories - insights for therapists. *Physiotherapy*, *83*, 397-405.

Bezerra, Í. M. P., Crocetta, T. B., Massetti, T., da Silva, T. D., Guarnieri, R., Meira, C. de M.,…Monteiro, C. B. de M. (2018). Functional performance comparison between real and virtual tasks in older adults: a cross sectional study. *Medicine*, 97, 4(e9612). http://dx.doi.org/10.1097/MD. 0000000000009612

Boutin, A., Badets, A., Salesse, R. N., Fries, U., Panzer, S., & Blandin, Y. (2012). Practice makes transfer of motor skills imperfect. *Psychological Research*, *76*, 611-625.

Bozzacchi, C., Spinelli, D., Pitzalis, S., Giusti, M. A., & Di Russo, F. (2015). I know what I will see: action-specific motor preparation activity in a pssive observation task. *Social Cognitive and Affective Neuroscience*, *10*, 783-789.

Breslin, G., Hodges, N. J., & Williams, M. A. (2009). Effect of information load on time on observational learning. *Research Quarterly for Exercise and Sport*, *80*, 480-490.

Broderick, M. P., & Newell, K. M. (1999). Coordination patterns in ball bouncing as a function of skill. *Journal of Motor Behavior*, *31*, 165-188.

Buchanan, J. J., & Dean, N. J. (2010). Specificity in practice benefits learning in novice models and variability in demonstration benefits observational practice. *Psychological Research*, *74*, 313-326.

Buchanan, J. J., & Wright, D. L. (2011). Generalization of action knowledge following observational learning. *Acta Psychologica*, *136*, 167-178.

Calabrò, R. S., Naro, A., Russo, M., Leo, A., De Luca, R., Balletta, T., … Bramanti, P. (2017). The role of virtual reality in improving motor performance as revealed by EEG: a randomized clinical trial. *Journal of NeuroEngineering and Rehabilitation*, *14*, 53-69. doi.org/10.1186/s12984-017-0268-4

Choi, G., Chung, H., & Kim, Y. (2012). Are stereotypes relative to gender usage applicable in virtual worlds? *International Journal of Human-Computer Interaction*, *28*, 399-405.

Coe, R. (2002). It’s the effect size, stupid: What effect size is and why it is important. *Proceedings of the Annual Conference of the British Education Research Association*. Education On-Line Database. https://www.leeds.ac.uk/educol/documents/00002182.htm

Eaves, D. L., Breslin, G., van Schaik, P., Robinson, E., & Spears, I. R. (2011). The short-term effects of real-time virtual reality feedback on motor learning in dance. *Teleoperators and Virtual Environments, Special Issue: Virtual Reality and Sports*, *20*, 62-77. http://dx.doi.org/10.1162/pres_a_00035

Farsi, A., Bahmanbegloo, Z. H., & Abdoli, B. (2016). The effect of observational practice by a point-light model on learning a novel motor skill. *Perceptual and Motor Skills*, *123*, 477-488.

Fu, Q., Hasan, Z., & Santello, M. (2011). Transfer of learned manipulation following changes in degrees of freedom. *The Journal of Neuroscience*, *31*, 13576-13584.

Guccione, A. A., Neville, B. T., & George, S. Z. (2019). Optimization of movement: A dynamical systems approach to movement systems as emergent phenomena. *Physical Therapy*, *99*, 3-9.

Harmsen, W. J., Bussmann, J. B. J., Selles, R. W., Hurkmans, H. L. P., & Ribbers, G. M. (2015). A mirror therapy-based action observation protocol to improve motor learning after stroke. *Neurorehabilitation and Neural Repair*, *29*, 509-516.

Hashimoto, Y., Honda, T., Matsumura, K., Nakao, M., Soga, K., Katano, K., …Ishikawa, K. (2015). Quantitative evaluation of human cerebellum-dependent motor learning through prism adaptation of hand-reaching movement. *PLoS ONE*, *10*, e0119376. DOI:10.1371/jounal.pone.0119376.

Iacoboni, M., & Mazziotta, J. C. (2007). Mirror neuron system: basic findings and clinical applications. *Annals of Neurology, 62*, 213-218.

Kai, S., & Watari, K. (2005). Intermanual transfer of effects of motor learning from the dominant to non-dominant hand using a grip force retaining task. *Journal of Physical Therapy Science*. *17*, 57-61.

Kim, A., Kretch, K. S., Zhou, Z., & Finley, J. M. (2018). The quality of visual information about the lower extremities influences visuomotor coordination during virtual obstacle negotiation. *Journal of Neurophysiology*, *120*, 839-847. http://dx.doi.org/10.1152/jn.00931.2017

Kitson, A., Sproll, D., & Riecke, B. E. (2016). Influence of ethnicity, gender and answering mode on a virtual point-to-origin task. *Frontiers in Behavioral Neuroscience*, *10*, 22. doi: 10.3389/fnbeh.2016.00022.

Latash, M. L. (1999). Mirror writing: Learning, transfer, and implications for internal inverse models. *Journal of Motor Behavior*, *31*, 107-111.

Latash, M. L. (2010). Stages in learning motor synergies: A view based on the equilibrium-point hypothesis. *Human Movement Science*, *29*, 642-654.

Levin, M. F., Weiss, P., & 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.

Ludolph, N., Giese, M. A., & Ilg, W. (2017) Interacting learning processes during skill acquisition: learning to control with gradually changing system dynamics. *Scientific Reports*, *7*, 13191. http://dx.doi.org/10.1038/s41598-017-13510-0

Magill, R. A. (2011). *Motor learning and control: Concepts and Applications*. 9th ed. Columbus, OH: McGraw Hill.

Morice, A. H. P., Siegler, I. Al, Bardy, B. G., & Warren, W. H. (2007) Learning new perception-action solutions in virtual ball bouncing. *Experimental Brain Research*, *181*, 249-265. http://dx.doi.org/10.1007/s00221-007-0924-1

Muratori, L. M., Lamberg, E. M., Quinn, L., & Duff, S. V. (2013). Applying principles of motor learning and control to upper extremity rehabilitation. *Journal of Hand Therapy*, *26*, 94-102.

Neva, J. L., Ma, J. A., Orsholits, D., Boisgontier, M. P., & Boyd, L. A. (2019). The effects of acute exercise on visuomotor adaptation, learning, and inter-limb transfer. *Experimental Brain Research*, *237*, 1109-1127.

Nojima, I., Mima, T., Koganemaru, S. Thabit, M. N., Fukuyama, H., & Kawamata, T. (2012). Human motor plasticity induced by mirror visual feedback. *Journal of Neuroscience*, *32*,1293-1300.

Norton, J., & Wolpaw, J. R. (2018). Acquisition, maintenance, and therapeutic use of a simple motor skill. *Current Opinion in Behavioral Sciences*, *20*, 138-144. http://dx.doi.org/10.1016/cobehav.2017.12.021

Ossmy, O. & Mukamel, R. (2016a). Activity in superior parietal cortex during training by observation predicts asymmetric learning levels across hands. *Scientific Reports*, *6*, 32133. https://doi.org/10.1038/srep32133

Ossmy, O. & Mukamel, R. (2016b). Neural network underlying intermanual skill transfer in humans. *Cell Reports*, *17*, 2891-2900.

Ossmy, O. & Mukamel, R. (2017a). Short term motor-skill acquisition improves with size of self-controlled virtual hands. *PLoS ONE*, *12*, 1(e0168520). http://dx.doi.org/10.1371/journal.pone.0168520

Ossmy, O., & Mukamel, R. (2017b). Using virtual reality to transfer motor skill knowledge from one hand to another. *Journal of Visualized Experiments*, *127*, e55965. http://dx.doi.org/10.3791/55965

Ossmy, O. & Mukamel, R. (2018). Behavioral and neural effects of congruency of visual feedback during short-term motor learning. *NeuroImage*, 172, 864-873. **"a"**

Ostry, D. J., Darainy, M., Mattar, A. A. G., Wong, J., & Gribble, P. L. (2010). Somatosensory plasticity and motor learning. *The Journal of Neuroscience, 30*, 5384-5393.

Pierce, W. D. & Cheney, C. D. (2008). Chapter 4 Reinforcement and extinction of operant behavior. In: *Behavior Analysis and Learning*, 4th ed. New York, NY: Psychology Press, 65 - 91.

Pineda, J. A. (2008). Sensorimotor cortex as a critical component of an 'extended' mirror neuron system: does it solve the development, correspondence, and control problems in mirroring? *Behavioral and Brain Functions, 4,* 47. doi:10.1186/1744-9081-4-47.

Prochnow, D., Badia, S. B., Schmidt, J., Duff, A., Brunheim, S., Kleiser, R.,…Verschure, P. F. M. J. (2013). A functional magnetic resounance imaging study of visuomotor processing in a virtual reality-based paradigm: rehabilitation gaming system. *European Journal of Neuroscience*, *37*,1441-1447. http://dx.doi.org/10.1111/ejn.12157

Ranganathan, R., Adewuyi, A., & Mussa-Ivaldi, F. A. (2013). Learning to be lazy: Exploiting redundancy in a novel task to minimize movement-related effort. *The Journal of Neuroscience*, *33*, 2754-2760.

Rao, H. M., Khanna, R., Zielinski, D. J., Lu, Y., Clements, J. M., Potter, N. D., …Applebaum, L. G. (2018). Sensorimotor learning during a marksmanship task in immersive virtual reality. *Frontiers in Psychology, 9,* 58. http://dx.doi.org/10.3389/fpsyg.0058

Rizzolatti, G., & Luppino G. (2001). The cortical motor system. *Neuron, 31,* 889-901.

Salmoni A. W., Schmidt, R. A., & Walter, C. B. (1984). Knowledge of results and motor learning: a review and critical appraisal. *Psychological Bulletin*, *95*, 355-386.

Shae, C. H., Kovacs, A. J., & Panzer, S. (2011). The coding and inter-manual transfer of movement sequences. *Frontiers in Psychology*, *2*, 52. doi: 10.3389//fpsyg.2011.00052.

Shae, J. B., & Morgan, R. L. (1979). Contextual interference effects on the acquisition, retention, and transfer of a motor skill. *Journal of Experimental Psychology: Human Learning and Memory*, *5*, 179-187.

Shumway-Cook, A., & Woollacott, M. H. (2007). *Motor control: Translating research into clinical practice*. Philadelphia, PA: Lippincott Williams & Wilkins.

Simones, L., Rodger, M., & Schroeder, F. (2017). Seeing how it sounds: Observation, imitation and improved learning in piano playing. *Cognition and Instruction, 35,*125-140.

Stefan, K., Cohen L. G., Duque, J., Mazzocchio, R., Celnik, P., Sawaki, L., …Classen, J. (2005). Formation of a motor memory by action observation. *Journal of Neuroscience, 25,* 9339-9346.

Stöckel, T. & Weigelt, M. (2012). Brain lateralisation and motor learning: Selective effects of dominant and non-dominant hand practice on the early acquisition of throwing skills. *Laterality*, *17*, 18-37.

Sullivan, K. J., Kantak, S. S., & Burtner, P. A. (2008). Motor learning in children: Feedback effects on skill acquisition. *Physical Therapy*, *88*, 720-732.

Taylor, J. A., Wojaczynski, G. J., & Ivry, R. B. (2011). Trial-by trial analysis of intermanual transfer during visuomotor adaptation. *Journal of Neurophysiology*, *106*, 3157-3172.

Thorndike, E. L. (1927). The law of effect. *American Journal of Psychology*, 39, 212-222.

Veale, J. F. (2014). Edinburgh Handedness Inventory - Short Form: A revised version based on confirmatory factor analysis. *Laterality*, *19*, 164-177.

Welch, R. B., & Sampanes, A. C. (2008). Adapting to virtual environments: visual-motor skill acquisition versus perceptual recalibration. *Displays*, *29*, 152-158.

Appendix A

Participant Intake Form

Instructions: Circle the appropriate responses below.

1. Age (in years): ____________

2. Gender: F M Other

3. What is your dominant hand? R L

4. Have you ever used an Oculus Rift virtual reality system? Yes No

5. Have you ever used another form of virtual reality device? Yes No

6. Have you been diagnosed with a neurological condition? (multiple sclerosis, stroke, traumatic brain injury, seizures, etc.)
Yes No

7. Have you been diagnosed with any psychological illness which could be aggravated through use of virtual reality? (post-traumatic stress disorder, claustrophobia, etc.)
Yes No

8. Do you wear corrective lenses? Yes No
If yes, answer questions 9-10. If no, skip to question 11.

9. Do you have difficulty seeing objects at: Far distances or Close distances or Both or Other

10. Are you currently wearing contacts? Yes No

11. Is there any reason you may be unable to use your arms to their full capacity?
Yes No

12. Do you have more ball throwing experience than the average person in the community? (baseball player, throw balls frequently for a dog etc.)
Yes No

13. Are you able to sit for up to 45 minutes without a break? Yes No

14. On average, how many hours per day do you spend playing video games, computer games, etc?

0-1 hrs 2-3 hrs 4-5 hrs 6-7 hrs > 7 hrs

Appendix B

Edinburgh Handedness Inventory – Short Form

Please indicate your preferences in the use of hands in the following activities or objects:

	Always right	Usually right	Both equally	Usually left	Always left
Writing	☐	☐	☐	☐	☐
Throwing	☐	☐	☐	☐	☐
Toothbrush	☐	☐	☐	☐	☐
Spoon	☐	☐	☐	☐	☐

Veale, J. F. (2014). Edinburgh Handedness Inventory – Short Form: A revised version based on confirmatory factor analysis. *Laterality*, *19*, 164-177.

Appendix C

Standardized Instruction Script Example: Pre-test

These instructions were used immediately after VR acclimation during the initial testing of ability to throw the virtual ball with each arm.

1. "Now I am going to measure how well you perform a virtual ball throwing task with each arm."
2. "I will open the task, orient you to how it works, and then you will attempt to throw a virtual ball at a stack of virtual blocks 10 times with each arm."
3. "I will keep track of each time the ball hits the blocks, even if it is a nudge."
4. "Please try to hit the stack of blocks as many times as you can during the 10 throws with each arm."
5. "This is the ball-throwing task. Please listen and look at the task while I orient you to how it works.
6. "There is a ball sitting in front of you. When you begin, you will pick up the ball with your **left** hand and then try to throw it at the blocks."
7. "When you would like a new ball, reach up and press the "Ball Back" button. When you would like a new ball and a new stack of blocks, reach up and press the "New Game" button."
8. "You will begin with your **left** hand. You will make 1 set of 10 throws. I will let you know when there are 2 remaining throws in the set of 10."
9. "You will have up to 1 ½ minutes to complete the 10 throws. If needed, I will let you know when 15 seconds remain."
10. "You will then repeat the same procedures using your **right** hand to perform 1 set of 10 throws."
11. "Any questions before you begin?"
12. "Begin the 10 throws with your **LEFT** hand now."
13. "You have 2 throws remaining in this set."
14. "You have 15 seconds left to complete this set of 10 throws." (Only use when applicable.)

18. "Begin 10 throws with your **RIGHT** hand now."
19. "You have 2 throws remaining in this set."
20. "You have 15 seconds left to complete this set of 10 throws." (Only use when applicable.)

24. "You have finished your first set of throws with each hand. Now you will begin the first training condition.

Appendix D

Session 1: Post-participation Questionnaire

Thank you for participating in the first session of this virtual reality study. Please read each question carefully and provide select the response that best fits your experience.

1. While performing the ball throwing tasks in this study, the majority of the time I felt:

   a. it was a fun task.
   b. it was a frustrating task.
   c. neutral – it was neither fun nor frustrating.
   d. other: explain ____

2. How would you self-rate your performance throwing the virtual ball at the target:

A. using your untrained **left arm?**	B. using your trained **right arm**?
a. I performed very well	a. I performed very well
b. I performed adequately	b. I performed adequately
c. neutral – neither great nor horribly	c. neutral – neither great nor horribly
d. I performed poorly	d. I performed poorly
e. I did absolutely horribly	e. I did absolutely horribly

3. How well do you expect to perform during Session 2 of this study?

A. With your untrained **left arm**?	B. With your trained **right arm**?
a. 0 – 1 hits	a. 0-1 hits
b. 2 – 4 hits	b. 2 – 4 hits
c. 5 – 7 hits	c. 5 – 7 hits
d. 8 – 10 hits	d. 8 – 10 hits