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DIFFERENTIATING SELF-REPORTED IMAGERY ABILITIES WITH FUNCTIONAL MAGNETIC RESONANCE IMAGING

by

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DEDICATION

To my family: There are no words to express how important you have been throughout this process. Thank you for all of your love and support while I pursued my professional goals. One day, I hope I can show you how integral you were these last four years.

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ABSTRACT

Motor imagery (MI), a top-down knowledge-driven process involving the deliberate cognitive simulation or rehearsal of an action without engaging in overt physical movements, shares the same neural networks as movement execution improving motor learning and enhancing performance of motor tasks. The capacity to form images is not universal, and is a variable, moderating factor of neural activity impacting intervention effectiveness and distinguishing between individual imagery abilities. Measuring imagery abilities through self-report measures (i.e., MIQ-3 and VMIQ-2) is common, but the importance of behavioral and neuroimaging techniques have also been highlighted. Despite the robustness of these questionnaires, few studies have investigated their biological validity. This is surprising given that these questionnaires are frequently used to determine participants' imagery abilities and adopting them in the neuroscience literature for screening purposes. Therefore, two studies were conducted to help extend present MI theories by examining the convergent validity of self-report questionnaires through fMRI. In the first study, 17 females aged 18-30 screened by the MIQ-3 as having good imagery abilities were recruited to examine the construct validity of the MIQ-3. Following an fMRI simulation session, participants were scanned to determine the neural networks active during KI, IVI, and EVI of the arm rotation task of the MIQ-3. Results revealed common and distinct brain activity providing initial biological validation for the imagery abilities delineated in the MIQ-3. For study two, an additional 17 participants aged 18-30 were screened as having poor imagery abilities. The task and procedure were identical to the previous study. As expected, both good and poor imagers had peak activations in the inferior parietal lobule and motor-related areas. Inter-group comparisons revealed that good imagers had greater activation in the frontal, parietal and premotor areas. By contrast, poor imagers recruited a wider neural network (i.e., middle frontal gyrus and subcortical areas). Overall, both studies provide central evidence for common and divergent neural networks of imagery abilities defined in the sport sciences. Future research should expand this body of literature to other tasks and male participants as well as investigate imagery abilities used to create cognitive and affective image content.

Key Words: Imagery Ability, MIQ-3, fMRI, Kinesthetic Imagery, Internal Visual Imagery, External Visual Imagery

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LIST OF ABBREVIATIONS

ANS	Autonomic Nervous System
BOLD	Blood Oxygenation Level Dependent
CNS	Central Nervous System
EEG	Electroencephalography
EMG	Electromyography
EVI	External Visual Imagery
fMRI	Functional Magnetic Resonance Imaging
IVI	Internal Visual Imagery
KI	Kinesthetic Imagery
MC	Mental Chronometry
MI	Motor Imagery
MII	Motor Imagery Index
MIQ-3	Movement Imagery Questionnaire-3
ME	Movement Execution
MEG	Magnetoencephalography
M1	Primary Motor Cortex
PET	Positron Emission Tomography
PMC	Premotor Cortex
rCBF	Regional Cerebral Blood Flow
SMA	Supplementary Motor Area

TMS	Transcranial Magnetic Stimulation
VI	Visual Imagery
VMIQ-2	Vividness of Movement Imagery Questionnaire-2

CHAPTER 1

INTRODUCTION AND REVIEW OF LITERATURE

Mental simulation is frequently regarded as a classical type of psychological training used to improve performance in a variety of movement contexts. Theoretically, mental simulation is largely focused on perception and experience, allowing one's mind to create a representation of an event or a series of events that have previously occurred, or that of a future scenario. In order for mental simulation to occur, it is argued that mental techniques and/or cognitive strategies for motor retrieval, motor planning/preparation, and mental execution must properly be utilized. One such technique that has received attention, with regard to the improvement on the acquisition of performance of motor skills, is imagery.

Broadly defined, imagery involves an individual imaging a self-performed action that is an internally generated, cognitive and spatial representation of an object or experience without the accompaniment of subjective sensations or overt movement (Moran, 2004). Further integrating concepts from information processing, perception and neuroscience research, imagery here is considered an ability resembling perception; consisting of internal representations produced from memory, similar to those during the initial phases of like-modality perception (Kosslyn, Ganis, & Thompson, 2001). Collectively, evidence shows imagery to be a strategy for enhancing various aspects of performance including skills, cognition and motivation (Hall, Mack, Paivio, & Hausenblas, 1998), as well as an adjunct to sport performance (Orlick & Partington, 1988). Imagery is considered a multidimensional (including implicit and explicit aspects) cognitive skill (McAvinue & Robertson, 2009) that has been extensively researched within many fields including sport, dance (Cumming & Ramsey, 2008), rehabilitation (de Vries & Mulder, 2007; Gregg, Hall & Butler, 2010) and allied health professions (Sanders et al., 2004; Speck, 1990), including athletic training (Monsma et al., 2011).

Aligned with the functional equivalence theory (Finke & Shepard, 1986) and simulation theory (Jeannerod, 2001), studies have shown that muscular (Bakker, Boschker, & Chung, 1996; Lutz & Linder, 2001) and neurological (Cuthbert, Vrana, & Bradley, 1991; Szameitat, Shen, & Sterr, 2007) activations are similar when physically performing or imaging the same movement. An accumulation of evidence suggests that individuals with better imagery skills (i.e., vividness and ease of generating images) benefit more from using imagery than those with poorer skills (Lawrence, Callow, & Roberts, 2013); learn better skills, executing fewer errors (Goss, Hall, Buckolz, & Fishburne, 1986), can perform skills faster (Borst & Kosslyn, 2010; Guillot & Collet, 2010) and experience positive affect (i.e., confidence and low anxiety) typically associated with competition (Gregg, Hall, & Nederhof, 2005) or high stakes assessments (i.e., competition and audition) (Gregg et al., 2005; Monsma & Overby, 2004).

Consistent with Paivio's (1985) early notion that imagery is an ability that improves with practice and that genetic variability may limit these effects, imagery ability (IA) is conceptualized in the sport and neuroscience literature in terms of imagery perspective and sensory specific modes where visual and kinesthetic imagery abilities are most relevant to, and frequently considered in movement context studies. That is, in a given sample, some participants report good imagery abilities in both visual and kinesthetic modes, others report poor imagery abilities in both, while others report good visual and poor kinesthetic, or, least likely, poor visual and good kinesthetic abilities. This variability has both methodological and practical importance. Because IA moderates the effectiveness of imagery interventions, design strategies such as stratifying experimental groups by IA should be common practice. Practically, coaches and educators should help athletes and students explore their IA strengths and weaknesses.

Imagery ability definitions vary across the literature and depend on the purpose for which the imagery description is used, challenging generalizability. With this, the validity of IA measures has been an important and ongoing topic in cognitive and sport psychology as well as neuroscience research paradigms where the content and structure of covert processes that precede the execution of action are considered (e.g., Decety & Grezes, 2006).Throughout this parallel evolution of imagery, there has been a great deal of debate regarding imagery's qualities and characteristics across several disciplines of imagery inquiry as well as it's convergent validity between two measurement procedures and research methods (i.e., pencil-and-paper and brain mapping) in order to support the use of common IA assessments. The utility of imagery characteristics discovered throughout research is that they serve as external prompts that if deemed effective, can be used in interventions geared at enhancing various motor performance attributes: skill learning, movement precision, anticipation of events and even emotional regulation in challenging situations.

The bulk of what we know about imagery measurement, especially in the sport science literature, rests on various psychometric iterations of two self-report inventories: the Movement Imagery Questionnaire (MIQ: Hall, Pongrac, & Buckholz, 1985) which measures the ease of generating images, and the Vividness of Movement Imagery Questionnaire (VMIQ: Isaac, Marks, & Russell, 1986) measuring the vividness of the imagery experience. Through psychometric validation processes, the VMIQ-2 (Roberts, Callow, Hardy, Markland, & Bringer, 2008) and MIQ-3 (Williams, Cumming, Ntoumanis, Nordin-Bates, Ramsey, & Hall, 2012) are the most current versions available and each instrument measures three scales (i.e., internal visual imagery, external visual imagery, and kinesthetic imagery) confirmed in factor analyses. Both questionnaires offer an efficient way of measuring IA but the fundamental difference between them is how they define IA, which may lead to inconsistent results across studies. Recently, the validity of imagery assessment has been questioned because of imagery scores not correctly classifying IA groups (van der Meulen, Allali, Rieger, Assal, & Vuilleumier, 2012).

Interestingly, these questionnaires have been adopted in neuroscience for screening purposes (e.g., Guillot et al., 2009) and testing intervention effects (e.g., Guillot et al., 2008; Roure et al., 1999). Despite their current use, it is currently unknown if objective measures (i.e., PET and fMRI) support the construct validity of the self-report IA measures in order to inform researchers about the efficacy of the continued use of the MIQ-3 and VMIQ-2. This is a logical next step because of the susceptibility of self-report measures to various types of bias, including social desirability and the ability of participants to modulate their behavioral responses under experimental conditions, impeding reliable measurements. However, using brain mapping techniques should limit participant's ability to manipulate their brain response during imagery and remove the variability in imagery ability from memory decay, which will help elucidate that individuals are imaging what they say they are imaging.

There is already evidence to suggest that motor imagery (MI) and movement execution (ME) share some of the same neural substrates (Decety, 1996; Hetu et al., 2013; Jeannerod, 2001). If a major goal of imagery is to enhance performance in sport and other skill-oriented settings, it is necessary for an individual to have good MI ability. It is vital that researchers continue their efforts of connecting subjective and objective imagery measures in order to map the theoretical construct of imagery onto brain areas. Therefore, the purpose of this study is to determine if there is convergent validity between self-reported IA and brain activation measured by fMRI which will further allow researchers and clinicians to reliably use self-report questionnaires.

The following literature review opens with a brief delineation between MI and ME, followed by a description of the neurological components that are important in motor control and ME, and thus important in MI. It is followed with a description and supporting evidence of the major theoretical frameworks used to explain the similarity between MI and ME. The subsequent section provides a comprehensive review of research on the qualities of imagery, specifically IA, how MI ability is measured, and individual differences that moderate the effectiveness of imagery. Finally, major limitations of the current literature are discussed along with an explanation of how this study will help advance the understanding of how to measure MI ability.

Intersection of Motor Imagery and Movement Execution

Researchers have examined many types of knowledge, including memory for movements (Engelkamp, Zimmer, Mohr, & Snellen, 1994). One way to recall and practice movement memories is through motor imagery (MI). In contrast to actual physical movement during movement execution (ME), MI has been recognized as a method that enables the mind to mentally simulate or rehearse an action without engaging in overt physical movements (Moran, Guillot, MacIntyre, & Collet, 2012; Olsson & Nyberg, 2010). Evidence indicates that MI is not a unitary constructed but one that is multidimensional in nature. Dimensions of imagery include the perceived ease or difficulty with which a participant generates movement images (Williams, Cumming, Ntoumanis, Nordin-Bates, & Hall, 2012), the ability to control and generate mental representations, and imagery vividness (McAvinue & Robertson, 2009). In order to provide learners with precise instructions on how to use imagery for motor performance improvements in athletics and other skill oriented disciplines, it is important to understand the intersection of MI and ME.

According to Jeannerod (1997, 1995), MI is a hierarchical model of action control. Within this model, it is argued that action includes the two covert stages of intending and planning/preparation, and the overt stage of execution. These stages of ME are important because MI has been considered a dynamic state during which a motor task is imagined in working memory without any overt motor output (Collet & Guillot, 2010; Decety, 2002; Decety, 1996). For example, in order to complete a reaching and grasping task, an individual first has to recall previous episodes with a similar goal in order to develop the intent to complete an action. This intention must then be translated into a set of internal commands, a programmed action sequence, which can be performed to satisfy the intention. For example, measuring regional cerebral blood flow (rCBF) with positron emission tomography (PET) Jenkins, Jahanshahi, Jueptner, Passingham, & Brooks (2000) found that imagery increased rostral SMA, anterior cingulate cortex and dorsolateral prefrontal cortex activation. Finally, the action sequence is physically executed (i.e., ME). At each stage, a conscious simulation of a motor representation (i.e., imagery) specifying the goal of the action is created to aid in its execution (Jeannerod, 2001; Jeannerod & Frak, 1999; McAvinue & Robertson, 2009, 2008). These representations are voluntarily controlled on the part of the imager, which goes beyond simply attending to an object of consciousness (Annett, 1995). Shepard (1988) refers to this feeling of having voluntary control as the subjective effort of imagined transformations, such that these internal manipulations use some of the same properties of overt, voluntary actions, including brain mechanisms (i.e., primary somatosensory cortex/postcentral gyrus and secondary sensorimotor cortex/superior parietal lobule).

Based on more recent research in cognitive psychology (Smith & Kosslyn, 2006), actions involve both covert and overt stages in which all overtly executed actions imply the existence of a covert stage, but covert actions do not necessarily have to produce an overt action (Jeannerod, 2001); that is, imagery does not always lead to action. This convergence between MI and ME is evidenced in the neuroscience literature that identified brain areas active during both MI and ME. These include the precentral gyrus, supplementary motor area (SMA) (rostral), cingular gyrus, and inferior parietal lobule (Decety et al., 1997; Gerardin et al., 2000; Lotze et al., 1999; Stephan et al., 1995). This similarity in brain activity indicates that when individuals engage in MI of a motor task, several brain areas for ME are already activated prior to physically completing the movement (See Table 1.1 for overlapping areas between MI and ME).

Table 1.1
Intersection of Active Brain Areas during MI and ME.

		Stages of Movement Execution		
		Overt Stage		Covert Stage
Brain Areas	Motor imagery	Intention	Planning/Preparation	Movement execution
Precentral gyrus	6, 7, 9, 11, 12, 13, 14			2, 5, 7, 8, 9
Precentral gyrus (dorsal)	2, 5, 6, 7, 10			1, 5, 7, 10
Precentral gyrus (ventral)	2, 10			1, 10
Superior parietal lobule				10
Premotor cortex/Premotor area			15, 16, 17, 18, 19, 20	
Supplementary motor area	23, 24, 25			
Supplementary motor area (rostral)	5, 6, 7		10, 21, 22	3, 7, 9
Supplementary motor area (caudal)				
Insular cortex			26	
Cingular gyrus	2, 5, 7, 10	4	27, 28, 29	1, 2, 5, 7, 8
Superior frontal gyrus	2, 5		30	
Middle frontal gyrus	2, 5, 6	4		
Inferior frontal gyrus	2, 5, 6			
Inferior parietal lobule	2, 5, 6, 10			1, 3, 7, 8, 10

Note. Numbers in the table correspond to those studies listed below indicating that they described activation in this particular area during each condition. (1) Binkofski et al. (1999); (2) Decety et al. (1997); (3) Faillenot et al. (1997); (4) Frith et al. (1991); (5) Gerardin et al. (2000); (6) Grafton et al. (1996); (7) Lotze et al. (1999); (8) Rizzolatti et al. (1996); (9) Roth et al. (1996); (10) Stephan et al. (1995); (11) Porro et al. (1996); (12) Munzert et al. (2008); (13) Sharma et al. (2008); (14) Tomasino et al. (2007); (15) Catalan et al. (1998); (16) Bischoff-Grethe et al. (2004); (17) Schubotz & von Cramon (2002); (18) Menon et al. (2000); (19) Schubotz & von Cramon (2001); (20) Dagher et al. (1999); (21) Jenkins et al. (2000); (22) Freund (1990); (23) Malouin et al. (2003); (24) Boecker et al. (2002); (25) Halpern & Zatorre (1999); (26) Beurze et al. (2007); (27) Wiese et al. (2004); (28) Heun et al. (2000); (29) Ruby et al. (2002); (30) Meister et al. (2004).

Imaging motor tasks is a cognitive skill that engages multiple parts of the motor system. The motor system includes lower and upper motor neurons, cerebellum, basal ganglia, and the motor cortex which are important in interpreting sensory signals and controlling voluntary movements. This central pattern of activation results in covert actions that correspond to the stages of ME, involving a true simulation of movements of one's own body (de Lange, Helmich, & Toni, 2006). On account of the continual activation of brain regions responsible for MI (i.e., primary motor cortex/precentral gyrus, SMA, and anterior cingulate gyrus) and ME (i.e., M1 and secondary sensorimotor cortex/superior parietal lobule) during each phase of action, it is logical that the intended, overt motor action would be facilitated.

Moreover, this overlap in motor cognition is possible because of the activation of the corticospinal pathway (Jeannerod, 2001). These pathways originate from the motor cortex and are important because they help shape the motor system by providing information from long term and working memory concerning potential actions, the anticipation of voluntary movements, and preparing specific responses. Functions of both long term and working memory are represented by overlapping networks that are associated with the retrieval, formation, and maintenance of the image (Tarkka & Stokic, 2013), which are necessary for MI as it activates a diverse neural network that overlaps with areas involved with ME. Therefore, the resulting image, and potential movement, reflects the representation displayed in working memory (Lorey et al., 2011). For example, neuroimaging studies have demonstrated that the SMA, M1, inferior parietal cortex, basal ganglia, and the cerebellum (Buccino et al., 2004, 2001;

Decety et al., 1994; Ehrsson, Geyer, & Naito, 2003; Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995; Gallese, Fadiga, Fogassi, & Rizzolatti, 1996; Gerardin et al., 2000; Strafella & Paus, 2000; Mushiake, Inase, & Tanji, 1991; Rizzolatti, Fadiga, Gallese, & Fogassi,1996; Rizzolatti, Fogassi, & Gallese, 2001) are activated in the early stage of motor control (i.e., planning/preparation). With specific activation, it places the action representation in a "true" motor format so that the motor system interprets it as a "real" action (Pascual-Leone et al., 1995). Since motor images cannot be separated from the motor generation process, MI and motor planning/preparation are proposed to have the same motor representation system in the brain (Jeannerod, 1994). Therefore, motor images should be involved in imagined movement allowing the generated motor representation to prime the intention and planning/preparation stages of an overt movement.

Research using temporal equivalence paradigms (i.e., the time for mental simulated movements being highly correlated with the time to actually make such movements) (Decety, Jeannerod, & Prablanc, 1989; Parsons, 1994), peripheral activity of the autonomic nervous system (ANS) (Decety, Jeannerod, Durozard, & Baverel, 1993; Decety, Jeannerod, Germain, & Pastene, 1991; Wang & Morgan, 1992; Wuyam et al., 1995), and various brain imaging techniques (Abbruzzese, Trompetto, & Schieppati, 1996; Holmes & Collins, 2001; Ingvar & Philipson, 1977; Lotze et al., 1999; Marks, 1999) have provided strong support for the overlap of common neural mechanisms of MI and ME. However, the extent to which these networks overlap is still a matter of debate. These shared neurological components, and the associated studies, which are relevant to both ME and MI, are discussed next.

Neurological Components Relevant to Motor Imagery and Movement Execution

The neurological components involved in MI have shown partially overlapping networks associated with ME (Gerardin et al., 2000). Voluntary movement, whether imagined or physically executed, is a specific type of movement which is learned, attended to, and based on a comparison among alternatives while being organized around the performance of a purposeful task. The selection of what joints, muscles, and body segments to use when executing a movement also depends on the goal of the movement. Within the human motor system, goal-directed movements are controlled by selecting the target of action, generating a motor plan, and coordinating the forces needed to achieve those objectives (Wise & Shadmehr, 2002).

The motor system consists of two interacting parts: peripheral and central. The peripheral motor system includes muscles and nerve fibers that are used for the actual execution of an overt movement, while the central motor system includes mechanisms throughout the central nervous system (CNS), including the cerebral cortex, basal ganglia, cerebellum, brain stem, and spinal cord that are responsible for higher-order characteristics of movements (i.e., sequencing and timing). The following sections will review the major components of the CNS that are relevant to MI. These systems include the (1) sensory system (somatosensory, viscerosensory, auditory, vestibular, olfactory, gustatory, and visual systems), (2) motor system (motor units, skeletal muscles, spinal reflexes, autonomic system, cerebellum, several subcortical and cortical sites, and the brain stem), and (3) systems responsible for homeostatic and higher brain functions; with the first two systems largely important in the imagery process.

These systems, and their components, are housed in specific cortices and gyri which are distinguished based on their function(s). Specifically, the frontal lobe is the largest lobe comprised of four gyri: the precentral gyrus, superior, middle and inferior frontal gyri. In addition, the frontal lobe consists of four general functional areas, including the primary motor area (M1: controls simple features of movements), premotor cortex (PMC) and SMA (responsible for learning sequences of discrete movements and selection of action), and the prefrontal cortex (implicated in planning complex cognitive behavior, short- and long-term decision making, creating strategies, attention, and concentration). The parietal lobe is comprised of three gyri: the postcentral gyrus (houses the primary somatosensory cortex), superior parietal gyrus (involved with spatial orientation), and inferior parietal gyri (interprets sensory information). The temporal lobe is formed by three oblique oriented gyri: the superior, middle, and inferior temporal gyri. These gyri are responsible for auditory processing, contemplating distance and recognition, and visual object recognition, respectively. Lastly, the most caudal aspect of the brain, the occipital lobe, is comprised of several irregular lateral gyri forming the primary visual cortex. Together, these cortices and gyri are organized into the cerebral cortex to functionally convey specific types of information to various areas of the brain in order to accomplish specific tasks; both physically and imagined.

MI is dependent upon the capacity of sensory, perceptual, and perceptual-motor functions stored in memory to physically execute a movement. However, the imagery process is not dependent on the actual ability to execute a task, but instead depends on the mechanisms of the human motor system. Thus, the overt execution of a movement cannot be completed unless the covert stages of intention and planning/preparation are present. For example, studies examining neurological rehabilitation patients (Butler & Page, 2006; Mulder, 2007; Page, Szaflarski, Eliassen, Pan, & Cramer, 2009; Sharma, Pomeroy, & Baron, 2006) found that patients unable to produce physical movement can use MI to activate the overlapping brain areas of ME. Evidence in this setting indicates that MI can be used for motor recovery when physical movement is contraindicated or not possible. These mechanisms have been predominantly examined using fMRI (measures functional brain activity by detecting associated changes in blood flow) and PET (measures functional processes in the body by detecting positron emitting radionuclides). Although both measure the functional properties of the brain, fMRI does not include the introduction of a nucleotide; rather it measures the associated changes in magnetization between oxygen-rich and oxygen-poor blood as a function of neural activity. For example, M1 represents a complex set of muscles and joints that make it possible for the cortex to organize combinations of movements to complete specific movements. Specifically, the neurons that are in M1 become active only shortly before and during voluntary movement. In contrast, the firing patterns of movement-related neurons in the PMC (responsible for planning movement, spatial/sensory guidance of movement, and understanding actions of others), are related to specific qualities of the movement being executed. These set-related neurons are active in the absence of any overt behavior, such as during a delay between task instructions and execution of the task, or during MI. The planning and execution of voluntary movements relies on sensorimotor transformations, which is the product of the PMC and M1 operating in conjunction with sensory and association areas (i.e., SMA) in order to integrate various representations into motor programs. This is illustrated by the communication between parietal and motor areas during various tasks (i.e., visually guided reaching) (Blohn, Keith, & Crawford, 2009; Kravitz, Saleem, Baker, & Mishkin, 2011), relying less on supplementary brain areas as the motor behavior becomes more well-known.

In a seminal fMRI study identifying the neural substrates mediating MI in good and poor imagers (n = 28), Guillot et al. (2008) demonstrated that the pre-SMA and SMA are active during the learning of a sequential finger sequence task but become less active as learning progresses. In addition, this behavior becomes more automatic, successively increasing activation in the PMC and M1 in both good and poor imagers. More specifically, both good and poor imagers recruited similar neural networks (i.e., inferior and superior parietal lobules, lateral and medial PMC, cerebellum, and putamen), but the pattern of activation of poor imagers showed a more widely distributed activation pattern (i.e., parietal, ventrolateral premotor areas, and cerebellum) compared to good imagers to compensate for their difficulties in eliciting a vivid mental representation of sequential movement; poor imagers used more of their brain, while good imagers used less with greater intensity. For the first time, imagery ability screening used a global imagery score involving the use of ANS (e.g., skin resistance responses), behavioral (e.g., Movement Imagery Questionnaire-Revised (MIQ-R)), auto-estimation and mental chronometry (MC) scores calculated with the following equation: (ANS score + MIQ-R score + auto-estimation score – (MC score)).

The importance of this study lies in the identification of good and poor imagers using a more rigorous pre-selection process that was able to provide greater reliability and convergent validity with brain imaging findings.

Several central mechanisms that appear to be important in human motor control have been studied in relation to MI. The phase of motor action where movement planning/preparation occurs activates the PMC/lateral premotor area (Bischoff-Grethe, Goedert, Willingham, & Grafton, 2004; Catalan, Honda, Weeks, Cohen, & Hallett, 1998; Menon, Anagnoson, Glover, & Pfefferbaum, 2000; Schubotz & von Cramon, 2002), SMA (rostral aspect) (Jenkins et al., 2000; Stephan et al., 1995), anterior cingulate cortex (Ruby, Sirigu, & Decety, 2002; Wiese et al., 2004) and the inferior parietal lobule/supramarginal gyrus (Meister et al., 2004). Movement initiation activates the SMA (caudal aspect) (Jenkins et al., 2000), while motor execution activates the superior parietal lobule and M1 (Stephan et al., 1995). Studies measuring rCBF (blood supply in the brain at a given time) have found a significant increase in blood supply in the premotor and frontal regions during MI (Ingvar & Philipson, 1977), as well as the SMA (Decety, Philippon, & Ingvar, 1988), cerebellum and basal ganglia (Decety et al., 1988; Decety, Sjoholm, Ryding, Stenberg, & Ingvar, 1990; Ryding, Decety, Sjoholm, Stenberg, & Ingvar, 1993). In addition, fMRI studies measuring the blood oxygenation level-dependent (BOLD) hemodynamic response show that M1, parietal lobe (specifically the somatosensory cortex), PMC, SMA, cerebellum (subcortical areas), and basal ganglia (Belardinelli, Palmiero, & di Matteo, 2009; Decety, 1996; Decety et al., 1990; Guillot & Collet, 2005; Guillot et al., 2008; Jeannerod, 2001; Hanakawa, Dimyan, & Hallet, 2008;

Higuchi, Imamizu, & Kawato, 2007; Lotze et al., 1999; Munzert, Lorey, & Zentgraf, 2009; Zacks, 2008) consistently play an important role in both ME and MI.

Functional MRI studies demonstrate that similar voxels (unit of analysis used in fMRI research representing single data points on a regularly spaced, three dimensional grid) activated during the contraction of a group of muscles (ME) are also activated during imagery of a movement involving the same muscles (MI) (Lotze et al., 1999; Munzert, Zentgraf, Stark, & Vaitl, 2008; Porro et al., 1996; Sharma, Jones, Carpenter, & Baron, 2008; Tomasino, Werner, Weiss, & Fink, 2007). To demonstrate neural mechanisms involved in imagery, specifically in participant who purport to have superior imagery abilities, Munzert et al. (2008) examined the activation of motor-related areas during MI of gymnastic movements. Participants were 10 right-handed female students that had good to very good imagery abilities (2.2 ± 0.8), as assessed by the Movement Imagery Questionnaire (MIQ: Hall & Martin, 1997). An overlap in activation for both ME and motor imagery in M1, PMC, and the SMA as well as the intraparietal sulcus, cerebellar hemispheres, and the basal ganglia using fMRI was found. Not only did this study corroborate the concept of overlapping core motor and motor-related areas during MI, it also served as construct validity evidence of the MIQ.

Sharma et al. (2008) specifically examined the extent and distribution of the M1 involvement during motor imagery compared to ME. Analysis of fMRI data using a voxel-based region of interest approach demonstrated that the anterior and posterior portions of M1 were both activated during motor imagery and ME of a right hand finger-thumb opposition sequence. Although M1 was activated to a lesser degree during motor imagery compared to ME, this study indicates that the activation of M1 is still similar to executed movement. These results are similar to earlier electromyography (EMG) studies that found comparable muscle activity during MI and ME of the same movement (Hale, 1982). Furthermore, other studies have also reported contralateral (to the imagined movement) activation of M1 during motor imagery (Gerardin et al., 2000; Lotze et al., 1999; Porro et al., 1996; Sharma et al., 2008).

Contradictory evidence from PET studies did not find significant activation in M1, such as in Stephan et al.'s (1995) study, during MI (Decety et al., 1994; Sharma et al., 2008). This study examined the differences in the distribution of rCBF of six healthy volunteers during ME and MI of a joy-stick movement. Results demonstrated that the medial and lateral premotor cortices, anterior cingulate cortex and parts of the superior and inferior parietal areas were all activated during MI. When comparing ME to MI the left primary sensorimotor cortex, medial and lateral PMC, cingulate areas, and left superior parietal cortex were also activated. These data indicate that imagined movements activate brain areas associated with the selection of actions associated with the planning/preparation phase of movement. While specific reports of activation during MI have been confirmed in similar brain areas compared to ME, the magnitude of activation is documented to be less than ME. For example, the activated voxels during MI in the contralateral M1 showed a reduction of about 50%, the contralateral somatosensory cortex of about 70%, and the anterior cerebellar lobule of about 30% compared to ME; while the SMA and PMC did not show any significant differences between MI and ME (Lotze et al., 1999; Porro et al., 1996).

Closely involved with M1 and the predominant areas involved in motor imagery are the PMC and SMA. Both are consistently reported as activations in MI studies (Guillot et al., 2008; Stephan et al., 1995), and are primarily involved in the planning/preparation of movement (Leonard, 1998). Particularly, the dorsal aspect of the PMC has been found to be involved in MI (Gerardin et al., 2000; Stephan et al., 1995). Orienting the body and preparing postural muscles, specifically motor sequencing/planning, working memory and observation of actions, are important functions produced by the PMC. For example, Decety et al. (1994), as well as others (Gerardin et al., 2000; Rizzolatti et al., 1996; Stephan et al., 1995), found significant activation of the dorsal and ventral aspects of the lateral part of the PMC during imagined hand movements. The same degree of overlap between covert and overt actions is also seen with the SMA which is important for the planning and production of complex movement sequences (Rosenbaum, 1991). Specifically, Stephan et al. (1995) found that MI neurons were located in the posterior rostral aspect of the SMA, whereas ME activated a caudoventral part of the SMA. Other studies confirmed these findings, and additionally demonstrated pre-SMA activation during MI (Gerardin et al., 2000).

In contrast, imagined movements have shown activation specifically concentrated in the rostral area of the SMA compared to executed movements (Gerardin et al., 2000; Lotze et al., 1999; Stephan et al., 1995). Nevertheless, motor learning (i.e. movement preparation/imagined movement and movement initiation) is controlled by the various parts of the SMA which projects primarily to M1 and brain stem motor areas. Together, M1, PMC, and SMA lead to fibers of the corticospinal tract, which is the primary pathway for the voluntary control of movement (Rose, 1997).

The associated cortical structures have also been found to be important in motor control and further studied in relation to MI. Specific subdivisions of the parietal cortex, including the inferior parietal lobule and the intraparietal sulcus, are activated during imagined grasping movements (Decety et al., 1994), decision making and action judgments (Parsons et al., 1995), and action observation (Buccino et al., 2001). During ME, these same parietal areas are also significantly recruited (Binkofski et al., 1999). Particularly, the posterior parietal cortex is important for transforming visual information into motor commands, including spatial localization of the body and external objects (Rosenbaum, 1991), as well as the storage and generation of action representations. Since this area integrates a large amount of visual and somatosensory information, it appears important for transforming object spatial coordinates and/or processing the constraints related to objects (Jeannerod, 2001). In addition, the prefrontal cortex is activated during the planning/preparation states when a decision has to be made preceding an overt action.

The subcortical structures of the cerebellum and basal ganglia are strongly activated during motor control. The basal ganglia appear to play a role in initiating movement and scaling movement parameters (Rose, 1997), and are found to be activated during both imagined and real actions; however, engaging different parts of the striatum (Gerardin et al., 2000). Specifically, ME has been shown to activate the putamen (sensorimotor coticocortical loop), while activation during MI involves the head of the caudate, which is part of a more cognitive loop. Lastly, the activation of the cerebellum during overt actions is consistent with that of the corticospinal system where it receives feedback from the spinal cord and cerebral cortex concerning movement (Shumway-Cook & Woollacott, 2001); therefore, it is strongly related with those activations of the sensorimotor cortex (Braitenberg, Heck, & Sultan, 1997). Cerebellar activation has been found to be involved in skill learning (Shumway-Cook & Woollacott, 2001) and during MI of simple hand movements (Decety et al., 1994; Ryding et al., 1993), allowing for the comparison of intended movement with actual movement commands in order to modulate movement (Morris, Spittle, & Watt, 2005). Activation of the cerebellum, including the medial and lateral aspects, is identified in imagined actions (Ryding et al., 1993), perceptually based motor decisions (Parsons et al., 1995), and during action observation (Lotze et al., 1999). An in-depth look at cerebellar activation revealed that areas activated during MI are located more posterior and inferior than those described during ME (Lotze et al., 1999).

Overall, it has been illustrated that MI and ME activate many of the same anatomical substrates including the motor and premotor cortices, SMA, parietal lobule, cerebellum, and basal ganglia, though to a lesser degree. Although recent studies are beginning to apply this concept to the study of larger body movements, we do not accurately know what characteristics alter and to what degree this activation is decreased in relation to ME. Regardless of the degree of overlap, MI has an important role in the overt phases of movement, as well as motor learning/control, motor sequencing, and movement initiation in order to prime the human motor system. The correspondence between brain areas activated by MI and ME is evident using two theories that have advanced the neurophysiological aspects in imagery research: functional equivalence theory and simulation theory.

Theoretical Framework

Previous theories (i.e., psychoneuromuscular, symbolic learning, and bioinformational) have generally been criticized for providing a vague or inadequate explanation for the underlying mechanism(s) of imagery, especially regarding performance benefits. The advent of more sophisticated neurophysiological measures has allowed researchers to gain a greater understanding of how imagery and movement overlap. Two theoretical frameworks that capture these overlapping aspects of movement and imagery and include neurophysiological measures to explain how imagery activates the brain are the functional equivalence theory (Farah, 1989; Finke, 1985, 1980; Finke & Shepard, 1986; Jeannerod, 1995, 1994) and simulation theory (Jeannerod, 2001).

Functional Equivalence Theory

As proposed by Marks (1977) “imagined stimuli and perceptual or ‘real’ stimuli have a qualitatively similar status in our conscious mental life” (p. 285). Ongoing research in cognitive psychology concerning how imagery functions has been guided by three broad theoretical categories, each focusing on different aspects between imagery and perception. First, structural theories focus on the similarities between the appearance of real and imagined objects. Kosslyn (1980) and Kosslyn, Pinker, Smith, and Shwartz (1979) used this type of theory to explain the spatial and pictorial properties of mental images (i.e., image-scanning tasks). Second, functional theories offer explanations of how the formation and transformation of mental images contributes to the process of comparing two objects (Shepard & Cooper, 1982). Functional theories are supported by mental rotation paradigms, a cognitive operation during which a mental image is formed and rotated into a different orientation in space, have been used to compare MI and ME in a temporal manner (Cooper & Shepard, 1973; Corballis, 1997; Pinker, 1980; Pinker & Finke, 1980; Shepard & Metzler, 1971). Mental rotation tasks measure performance by response time and accuracy usually requiring cognitive manipulation and spatial transformation of an object or body parts. Lastly, perceptual theories try to explain how imagery influences ongoing perceptual processes (Segal & Fusella, 1970); for example, how information from others and the situation guide future actions. Collectively, these are important to movement qualities because of the varying perspectives learners and athletes must possess in their visual field. As a relatively new area of research in neuroscience, the idea of accessing processes that correspond to thinking and feeling (i.e., cognitive or mental states) is characterized by the absence of overt actions and consists of mental representations and propositional attitudes. Propositional attitudes are relational mental states connecting a person to a proposition, which are often assumed to be the simplest components of thought. This coupled with concerns of early imagery theories led to the development of the functional equivalence theory.

According to the functional equivalence theory, the properties of motor images are analogous to ME (Farah, 1989; Finke, 1985, 1980; Finke & Shepard, 1986; Jeannerod, 1995, 1994); wherein “imagery draws on the same neural network that is used in actual perception and motor control, which may also activate neural circuits in memory and emotion” (Kosslyn, Ganis, & Thompson, 2001, p. 299). A key idea is that imagery mimics perception allowing for the organization, identification, and interpretation of mental information in order to represent and understand the environment (Smith & Kosslyn, 2006). Technological advances in cognitive neuroscience have enabled researchers to examine the degree of overlap by measuring brain activity. This overlap between imagery and perception has been observed in visual imagery (VI) (Kosslyn, Thompson, & Alpert, 1997), auditory imagery (Halpern & Zatorre, 1999), and olfactory imagery (Djordjevic, Zatorre, Petrides, Boyle, & Jones-Gotman, 2005). Because of this overlap, Kosslyn et al. (2001) suggested that imagery has the capacity to re-present a specific perceptual stimulus or situation, truly allowing an individual to experience what is cognitively occurring. Because it originated in cognitive psychology, the functional equivalence theory typically references the perception of sensory information, but methods (i.e., MC) have revealed that motor images retain several properties which are observed in the corresponding ME allowing for the perception of real action.

The bridge joining MI and ME is based on the notion that the brain stores memories in the form of mental representations. The idea that a central representation system mediates imagery is borrowed from the symbolic learning theory declaring that these mental representations can then be similarly accessed through actual and imagined behavior (Holmes & Collins, 2001). From the psychoneuromuscular theory, the functional equivalence theory borrows the idea that imagery activates small muscle contractions in order to strengthen cognitive skills and provoke psychophysiological responses to images. Furthermore, the bioinformational theory provides a link to the physiological responses (i.e., heart rate and skin conductance) to images as an individual's body elicits similar responses during a real or imagined experience (Hall, 2001; Holmes & Collins, 2002, 2001).

Initial evidence for this theory was found by Ingvar and Philipson (1977). Through measuring rCBF, it was found that similar areas of the brain (i.e., premotor and frontal regions) were activated when participants imagined clenching their hand or actually performing the task. These results highlight that the formation of abstract concepts can be accessible and quantified. In addition, Decety and colleagues (1994, 1990) investigated the common neural mechanisms between MI and motor preparation finding that both activated the SMA, PMC, and M1. Subsequently, comparable results were found by Lotze et al. (1999) examining executed and imagined movements of the left and right hand using fMRI. For example, if a participant imagines the planning/preparation of a movement the PMC and SMA will be activated, similar to physically preparing the same movements (Jenkins et al., 2000). Additional experiments in conjunction with evidence from previous studies provide strong support for the concept that MI and ME engage many of the same neural processes (see Hall, 2001; Murphy, Nordin, & Cumming, 2008). This suggests that MI should strengthen the mental representations for the planning/preparation stage of a motor task, and perhaps the generation and execution of these tasks (Abbruzzese et al., 1996). Although the functional equivalence theory appears to be effective in explaining imagery, especially how MI enhances motor skills, it is not without limitations.

Overall, the functional equivalence theory provides a more socio-physiological explanation of MI (Holmes & Collins, 2001), taking advantage of specific perceptual experiences to produce functionally equivalent images. Because it only proposes that MI draws on similar networks used in actual ME, especially during the planning/preparation phase of movement, it can only explain this similarity in terms of fundamental brain functioning. Therefore, it cannot specifically explain a similarity, in neural terms, between the simulated state of an action and the execution state of that action. Since MI is different than the perception of images, the introspective kinesthetic feelings of movement (Jeannerod, 1994) are imagined. Therefore, Jeannerod (1994) suggested that MI can be compared with movement planning/preparation, without indicating a functional equivalence of MI and ME.

Physiological and neurological research has only started to use neurophysiological approaches to compare imagery of complex movement tasks with the actual execution of those tasks. Not only does previous research illustrate that MI utilizes the PMC and basal ganglia, but it also relies on activation of the parietal and temporal areas as well as parts of the frontal cortex (i.e., M1, SMA, and pre-SMA) indicating that the imagery process is not localized to specific parts of the brain. Specifically, motor control is vastly distributed throughout the CNS; therefore, many brain areas will play a role depending on the complexity of the motor task (Jeannerod, 1995). This tendency has been found in studies using brain imaging methods to localize the activation sites of MI (Decety et al., 1994; Decety & Ingvar, 1990; Fox, Pardoe, Petersen, & Raichle, 1987; Ingvar & Philipson, 1977; Posner & Raichle, 1994; Roland et al., 1980); illustrating that MI involves a widely distributed cerebral network of structures. In addition, this theory explains imagery when it occurs as part of motor planning/preparation, driven by research showing that MI mostly activates similar brain regions for these stages of movement (Decety et al., 1994; Decety et al., 1990; Jeannerod, 1994), but not the actual movement itself. Lastly, a fundamental limitation of the functional equivalence theory is that it has not been directly linked to applied topics in sport psychology such as performance enhancement. To further advance the literature supporting a central mechanism responsible for MI and ME, the simulation theory was proposed by Jeannerod (2001) to provide insight into the covert stages of action; specifically, that covert actions are in fact actions, except they are not executed.

Simulation Theory

Like the functional equivalence theory, the simulation theory predicts the overlap of brain activity between MI and ME, while also addressing that motor structures of the brain are activated in a way that resembles activity during a normal action but does not cause any overt movements. Unlike functional equivalence, simulation theory specifically indicates that an individual engaging in action simulation replays past experiences in order to elicit perceptual activity (i.e., movement information) that resembles activity that would occur if the action is actually being performed. More recently, cognitive psychology, specifically human motor cognition research proposed that all actions involve a covert stage. This covert stage of action is considered a representation of the future, including the goal of the action, the means to achieve this goal, and the consequences it has on the individual and external environment. According to Jeannerod (2001) the simulation theory hypothesizes that the motor system is part of a “simulation network that is activated under a variety of conditions in relation to action” (p. S103). This theory reinforces the idea that covert and overt movements closely overlap (Smith & Kosslyn, 2006), demonstrating that images are actions minus the overt movement. Movement execution and MI are both driven by the same levels in the CNS, where MI is considered an “offline” operation of the motor areas in the brain (Gentili, Papaxanthis, & Pozzo, 2006; Jeannerod, 2001; Mulder, 2007). Not only does this theory include the intending actions that will be executed in the future, but it also includes imaging actions, recognizing tools, and learning by observation, which the functional equivalence theory was lacking. More importantly, the simulation theory accounts for all phases of ME where the functional equivalence theory focuses only on the overall brain areas that become active between an image and the actual task.

The idea that certain cognitive states are linked to simulated actions is not a new concept. Like the functional equivalence theory, the simulation theory was developed according to evidence illustrating that imagined movements retain the same temporal characteristics (i.e., MC of walking) as the corresponding real movement (Decety & Jeannerod, 1996; Decety et al., 1989). This is based on Fitts’s Law (Fitts & Posner, 1967), which governs that there is an inverse relationship between the difficulty of a movement and the speed that it is performed. This temporal similarity becomes obvious with tasks such as mental reciprocal tapping on targets of various sizes (Sirigu et al., 1995) and grasping objects placed at different orientations (Frak, Paulignan, & Jeannerod, 2001). Recent research has supported the temporal congruence of imagined and executed movements using difficulty as an independent variable with gross body movement such as gait (Bakker et al., 2008; Iseki, Hanakawa, Shinozaki, Nanakaku, & Fukuyama, 2008; la Fougere et al., 2010; Wang et al., 2009). Therefore, it is not surprising that MI involves an individual's "motor brain" and similar neural mechanisms as ME (Jeannerod, 1997, 1994).

As a result of mapping brain activity and measuring cortical excitability and activity of peripheral effectors, evidence has been provided relating to a subliminal activation of the motor system during these cognitive states. Support provided by mental chronometric studies show similar regularities observed in executed movements that are also retained in their covert counterparts. Mental chronometry involves the use of response time to infer the content, duration, and temporal sequencing of cognitive tasks. This approach has enhanced our understanding of imagery and ME mechanisms because it helps elucidate mechanisms underlying cognitive processing (Lotze et al., 1999).

Additional support for the simulation theory comes from findings in the neurophysiology research measured by neuroimaging techniques (i.e., fMRI). Jeannerod (2001) illustrated that while activation networks partially overlap, they differ from one simulation state to another as well as between covert and overt movements. The activations of these networks in the motor system are considered a prerequisite for the simulation theory. Generally, it has been demonstrated that M1, corticospinal pathways, basal ganglia, cerebellum, PMC, and SMA brain regions (Binkofski et al., 1999; Buccino et al., 2001; Chao & Martin, 2000; Decety et al., 1997, 1994; Failenot, Toni, Decety, Gregoire, & Jeannerod, 1997; Gerardin et al., 2000; Grafton, Arbib, Fadiga, & Rizzolatti, 1996; Hari et al., 1998; Lotze et al., 1999; Perani et al., 1995; Rizzolatti et al., 1996; Stephan et al., 1995) of the motor system have been activated to varying degrees during simulation states in the following conditions: execution, intention, imagination, action observation, and object observation. In addition, the parietal areas caudal and ventral to the primary parietal cortex are consistently activated during simulation states as well as during ME (Binkofski et al., 1999; Failenot et al., 1997; Jeannerod, 2001;); particularly during imagined grasping movements (Decety et al., 1994; Grafton et al., 1996), perceptually based decisions and prospective action judgments (Johnson, 2000; Parsons et al., 1995), action observation (Buccino et al., 2001; Grafton et al., 1996), and visual presentation of graspable objects (Chao & Martin, 2000).

This pattern of results illustrates that a covert action corresponds to the central stages of action, involving a true simulation of movements to one's own body (de Lange et al., 2006). On account of the continual activation of simulation states during all aspects of action, it is logical that the following overt motor action will be facilitated. This, in turn, helps shape the motor system by providing information concerning potential actions, as well as the anticipation of action in the planning/preparation phase of movement. Because of the unifying nature and the hypothesis that MI and ME are both guided by high levels of CNS activity, the simulation theory will drive the present study which intends to refine the connection between self-reported aspects of imagery ability and the overlapping neural activity that theoretically support them. To this end, it is important to consider imagery qualities that vary within and between individuals.

Qualities of Imagery

Imagery Perspective

Internal and external perspective delineations of the imagery experience are seminal qualities that have long been considered in both sport and neuroscience literature. Mahoney and Avener (1977) originally argued that imagery is a special type of mental simulation based on the visual representation, either through an internal (first-person) or external (third-person) perspective, of a movement action to optimize the conditions of external realization. The difference between the two is that in a third-person perspective an individual watches himself or herself performing the action from an observer's position; as if watching himself or herself on television (Hall, 2001; Mahoney & Avener, 1977; McAvinue & Robertson, 2008). It relies more on visuospatial processing, involving a visual representation of an action or the space in which the action takes place (Mahoney & Avener, 1977). For this reason, external imagery is considered a truer form of VI (Hall, Rodgers, & Barr, 1990; Janssen & Sheikh, 1994; White & Hardy, 1995), having stronger effects on the acquisition and performance of skills that depend on form for their successful completion (Hardy, 1997; White & Hardy, 1995). In comparison, the internal perspective involves an individual imagining himself or herself performing a movement as if they were actually performing the movement and looking through their own eyes (Hall, et al., 1990; Janssen & Sheikh, 1994; Mahoney

& Avener, 1977; White & Hardy, 1995). Internal imagery refers to an experience either inside or outside of the body that is not concerned with the sensory modalities (Denis, 1985). Therefore, it has been proposed that the internal imagery perspective is superior for the acquisition and performance of open skills because these skills significantly depend on perception and anticipation for their successful completion (Hall, 2001).

Research has generally shown that individuals usually prefer either an internal or external imagery perspective when engaging in imagery (Hardy & Callow, 1999; Mahoney & Avener, 1977; Spittle & Morris, 2007), with some specifically recommending internal imagery (e.g., Hale, 1998). However, what we currently know about perspective has emerged from important study design features. Early research examining the effect of internal and external imagery perspectives on motor performance and learning have shown equivocal results. An evaluation of the literature found that initial studies suggested that elite athletes favored internal imagery (Hall, 2001). For example, Mahoney and Avener (1977) completed a study on the U.S. Olympic gymnastics team showing that those who qualified used internal imagery more than non-qualifiers. Supporting evidence was found in a study of elite skiers (Rotella, Gansneder, Ojala, & Billing, 1980) and elite rowers (Barr & Hall, 1992); elite athletes preferred an internal imagery perspective. Contrary to these results, other studies have failed to support this idea (Hall et al., 1990; Hardy, 1997; Highlen & Bennett, 1979; Meyers, Cooke, Cullen, & Liles, 1979; Ungerleider & Golding, 1991; White & Hardy, 1995). For example, Meyers et al. (1979) found no significant differences in imagery perspective between more or less successful racquetball players, while Ungerleider and Golding (1991) found that successful U.S. track and field athletes used external imagery more than internal imagery.

The use of objective psychophysiological measures (i.e., EMG, cardiovascular response, metabolic responses, and perceptual responses) also differentiates imagery perspectives supporting the construct validity of frequently using self-report measures. For example, Shick (1970) measured electrical activity produced by the anterior deltoid and tibialis anterior muscles during mental practice of volleyball skills. Results did not indicate any significant EMG patterns between internal or external imagery. However, participants did say that they used an external perspective more while imaging a volleyball serve, but they changed their perspective to internal when total body was mentioned during the action of volleying. A related study by Harris and Robinson (1986) examined whether muscle innervation was specific to muscles that were needed for performance during internal and external imagery of karate tasks. Using 36 karate students, it was found that more EMG activity was produced during internal imagery than external imagery. Additional analyses revealed that advanced karateists favored an internal imagery perspective more than beginners and that they reported switching from internal to external imagery depending on the task. Moreover, Wang and Morgan (1991) examined the internal and external imagery of undergraduate and graduate participants’ (n = 30) psychophysiological responses of imagery perspective during four conditions (internal imagery, external imagery, actual exercise, and rest) of a dumbbell curl. Although some responses to external and internal imagery were like those occurring during actual exercise, the psychophysiological responses during internal imagery resembled actual exercise more than external imagery. These studies imply that imagery does excite muscles involved in the events imagined and is greater in the internal imagery perspective compared to the external imagery perspective, which may be a result of internal imagery containing a large kinesthetic component (see Hall, Schmidt, Durand, & Buckolz, 1994). However, all studies did mention that there was a lack of control in maintaining the desired perspective with participants switching perspectives during imagery.

On the other hand, unclear results were found in studies by Blair, Hall, and Leyshon (1993) and White and Hardy (1995). First, Blair et al. (1993) investigated the effect of an imagery training program on soccer performance of skilled (n = 22) and novice (n = 22) players that were equally and randomly assigned to an experimental or control group. Participants in the experimental group completed a six-week imagery program that included both visual and kinesthetic imagery as well as internal and external imagery perspectives, while the control group developed a competitive strategy. Response time and performance accuracy measurements were collected after the imagery training program illustrated a significant improvement for both skilled and novice players in the imagery group for response time, but not for performance accuracy. Additional research examining the speed of performance was completed by White and Hardy (1995) in experiments examining the efficacy of different imagery perspectives on a wheelchair slalom task and pseudo-gymnastic routine. Twenty-four students were separated into an internal imagery and external imagery group in which they completed the Vividness of Movement Imagery Questionnaire (VMIQ), which measured the vividness of internal and external visual imagery. The experiment consisted of watching an individual completing the task, then completing 3 blocks of 5 trials of the task with feedback after each and engaging in internal/external imagery before each trial. Average participant VMIQ scores were: internal visual imagery (IVI) = 92.33 and external visual imagery (EVI) = 89.33. Mixed results were found depending on the task; the external group focused on the speed of performance, while the internal group focused on the accuracy of performance during the slalom task suggesting that internal imagery is more effective at planning movements in response to changes in the visual field. On the other hand, external imagery was more effective for both learning and retention compared to internal imagery for the gymnastics task. These results indicate that internal imagery may not be beneficial for learning and performing a complex movement skill that include immediate body space compared to those based on time. Nevertheless, perspective matters and preferences appeared to be linked to task type.

These results generated addition research investigating the efficacy of different imagery perspectives on form dependent tasks (Hardy & Callow, 1999). Comparing internal imagery and external imagery, three experiments were completed with karateists (simulating fighting forms), gymnasts (simulating a floor routine), and high ability rock climbers (simulating boulder problems) finding that external imagery was more effective in all studies. These experiments support the idea that external imagery has greater effects on performance of skills that depend on form for their successful completion. A subsequent study by Cumming and Ste-Marie (2001) examined 18 female skaters participating in a five-week imagery training program that concentrated on the form of skating skills. Skaters identified their preferred perspective and were required to use this perspective throughout the imagery training program, but results revealed that imagery perspective had no significant effects. This indicates that self-choice of perspective may be mismatched with task demands or that the skater's perspective shifted (Harris & Robinson, 1986; Shick, 1970; Wang & Morgan, 1992); skaters using internal imagery for a form-contingent task confounded the results.

Imagery perspective distinctions have also been examined in the neuroscience literature where delineations are further supported by the use of objective measures. Ruby and Decety (2003) investigated the effect of perspective on the neural network engaged during mental simulation of action. Ten males (right-handed) participated in a PET activation protocol in which they were scanned during four conditions (two auditory and two visual) and two control conditions (one auditory and one visual) in order to identify the regions activated during internal and external simulation, as well as the common areas involved with internal and external imagery perspectives. Results showed that both internal and external perspectives activated the SMA, pre-central gyrus, precuneus and extrastriate visual area (MT/V5). When comparing the external perspective to the internal perspective the right inferior parietal, precuneus, posterior cingulate and frontopolar cortex were recruited. However, when comparing the internal to the external imagery perspective the left inferior parietal and somatosensory cortexes were activated. It was concluded that the inferior parietal, precuneus and somatosensory cortex are specifically involved in producing self-action (internal or first-person) compared to those generated by others (external or third-person), but these results only specified foci of activation (x, y, z coordinates) without indicating the depth or breadth of activation in these brain areas. Perspective differentiation has also been supported by neurological measures such as transcranial magnetic simulation (TMS: noninvasive method to cause changes in the neurons of the brain) and electroencephalography (EEG). When investigating, the corticospinal facilitation of 30 participants (18 females and 12 males) during internal and external imagery of an observed skill, scores for both measures were largest under the external imagery condition (Fourkas, Avenanti, Urgesi, & Aglioti, 2006). These findings continue to point to the importance of perspective as well as controlling the task condition; tasks that are short in duration and involve observing a skill prior to engaging in imagery are an important consideration in designing studies.

To further uncover imagery qualities that may be important in practical contexts, studies have considered visual and kinesthetic imagery modes concurrently with the assessment of perspectives. For example, Callow and Hardy (2004) examined the strength of the relationship between internal and external imagery and kinesthetic imagery (KI), as assessed by the MIQ and VMIQ, among 56 participants (28 females and 28 males) who were educated about these delineations during a three hour imagery workshop. A correlation analysis showed that although in the positive direction, correlations between internal imagery and KI ($r = 0.41$) and external imagery and KI ($r = 0.15$) did not reach significance ($p < 0.01$), suggesting that mode and perspective were measuring different aspects of imagery. In addition, result showed that females compared to males may have had a better composite imagery ability as measured by the VMIQ (106.8 ± 24.53, 105.9 ± 25.03, respectively), and the MIQ (43.36 ± 14.78, 46.26 ± 15.29, respectively). This finding illustrates the importance of controlling for gender in research designs and that male athletes benefit from learning more about imagery modes and perspectives if the goal is to improve their imagery ability. In study two, participants completed the same measures and procedure as study one, except that the instructions were changed to make the actual participant (compared to somebody else) the focus of the external imagery perspective. Results indicated a significant correlation between external and kinesthetic imagery ($r = 0.60$, $p < 0.01$), but not for internal and kinesthetic imagery ($r = 0.23$, $p < 0.01$). Therefore, external imagery may be used in conjunction with KI, while no support was provided for internal imagery being easier to perform with KI.

These findings prompted Calmels, Holmes, Lopez, and Naman (2006) to examine the temporal functional equivalence of internal and external imagery and action execution of 16 female elite gymnasts (Mean = 14.5, SD = 1.63) participating at the national level. Participants were separated into two groups (internal group = 10 and external group = 6) before completing the experiment (i.e., Yurchenko vault) by the French version of the VMIQ, verbally reporting the perspective used in training, and a sport psychologist assessment. A 2 x 3 x 2 (Perspective x Trial x Condition) ANOVA with repeated measures did not show an interaction ($F = 1.214$, $p = 0.31$) or a main effect for perspectives ($F = 1.475$, $p = 0.24$), trials ($F = 0.417$, $p = 0.66$), or conditions ($F = 2.631$, $p = 0.13$) for the full vault. In addition, results showed that the time taken to complete the vault between internal imagery (Mean = 4.91, SD = 1.95) and physical performance (Mean = 5.84, SD = 0.40), and external imagery (Mean = 5.65, SD = 1.49) and physical performance (Mean = 6.29, SD = 0.40) both did not significantly differ. However, when the action was divided into segments there was a significant difference between the imagery conditions compared to the physical condition. Thus, if the purpose of the study is to examine perspective differences, the time it takes to complete the task and imagery of that task may confound the results; therefore, a shorter and simpler task may be beneficial in some cases.

Recently, Callow, Roberts, Hardy, Jiang, and Edwards (2013) completed three experiments using three different slalom tasks (driving-simulation, downhill running, and downhill ski) in a virtual reality setting to determine which imagery perspective indicated better performance. For all three studies, measures of response time and imagery ability (determined by the VMIQ-2) were completed where internal consistencies for perspective and imagery mode scales were 0.86 for EVI, 0.90 for IVI, and 0.84 for KI. Experiment one separated 45 right-handed male participants (Mean = 21.35 years, SD = 3.12 years) into three groups (IVI, EVI, and KI) and examined the response time of completing a driving-simulation slalom task. Preliminary analyses of the VMIQ-2 data revealed no differences between groups for IVI ability F (2, 42) = 0.42, $p = 0.66$, $\eta^2 = 0.02$, 1-β = 0.11, and KI ability F (2, 42) = 1.32, $p = 0.28$, $\eta^2 = 0.01$, 1-β = 0.27. However, significant differences were found between groups for EVI, F (2, 42) = 7.48, $p = 0.002$, $\eta^2 = 0.26$, 1-β = 0.93, showing better EVI ability than the IVI group ($p = 0.003$) and control group ($p = 0.009$). A mixed-model ANOVA for performance (i.e., response time) indicated that the IVI group performed significantly better (i.e., quicker response times) than the EVI group ($p < 0.05$). Experiment two consisted of 22 sports science students (Mean = 22.5 years, SD = 3.08 years; 18 males and four females) with no significant difference in imagery ability across perspectives ($p = 0.31$). Results revealed that the movement task (i.e., downhill running slalom task) was completed significantly quicker using IVI than EVI ($p = 0.008$), but no differences were found for accuracy. Finally, 30 recreational skiers (Mean = 24.79 years, SD = 4.77 years; 23 males and seven females) were separated into an IVI, EVI, or control group and completed a slalom skiing task in experiment three. Results from single factor ANOVAs revealed a significant difference for accuracy (F (2, 23) = 3.59, $p = 0.04$, $\eta^2 = 0.24$, $1\text{-}\beta = 0.61$); the IVI group was more accurate than the control group. However, no differences were found between groups for response time (F (2, 23) = 1.22, $p = 0.32$, $\eta^2 = 0.10$, $1\text{-}\beta = 0.24$). Although these results support the beneficial effect of IVI on slalom tasks, KI was not included as its own condition and was not controlled during the other conditions. Nevertheless, this study illustrated the importance of task characteristics, employing specific imagery ability criteria, and the use of three different but linked tasks across the different experiments further advancing the imagery perspective literature.

Within the sport psychology literature, research regarding perspective has helped refine researchers’ choices of design details in order to provide support for what imagery perspective is more beneficial for motor performance. Within these studies, the type of task is important to consider (e.g., complex vs. simple, short vs. long, form-based vs. task-based) because of how they influence each perspective differently and limit the findings of these tasks (Hardy, 1997; Hardy & Callow, 1999; White & Hardy, 1995). In addition, the instructions provided to participants concerning the task and the nature of the study have led to confusion between the two perspectives. Situation dependent, individuals choose to use either an internal or external perspective through a visual or kinesthetic modality (Mahoney & Avener, 1977). Therefore, the imagery perspective needs to be explicitly communicated to participants or asked after engaging in imagery (i.e., “debriefing”) so that results are reliable and valid. Also, depending on the dependent measure examined (i.e., response time, accuracy, and/or questionnaire score) results may vary between the effectiveness of internal and external imagery for the task (Blair et al., 1993). Despite the details concerning experimental design that have emerged from the imagery perspective research, the neurological activation between internal and external imagery remains unknown, especially when participants are instructed to only engage in one perspective. In addition to perspective, imagery modality is important because it can provide discrete information relating to the purpose of imagery or the type of sport skill being learned or performed.

Imagery Modalities

Imagery modality refers to perceptual experiences tied to the five senses: visual, kinesthetic, olfactory, auditory and tactile with the first two being most relevant to motor tasks. The visual and kinesthetic systems are involved not only when watching examples of movements (Darling & Miller, 1993; Guillot et al., 2009; Neuper, Scherer, Reiner, & Pfurtscheller, 2005), but when perceiving what a movement would look like and feel like when based in instructions (Annett, 1995; Lotze & Halsband, 2006). It is not surprising that regardless of task experience, athletes often report using visual and kinesthetic imagery, often to the same extent (Murphy et al., 2008). Even though visual and kinesthetic imagery are used equally, neurophysiological data support the distinction between these modalities with the brain activating visual neural patterns during VI and motor neural patterns during KI (Annett, 1996; Berthoz, 1996; Decety, 1996; Farah, 1989; Holmes & Collins, 2001). Because of their use and subsequent neurological distinction, both visual and kinesthetic imagery have streamlined to the forefront of practical applications used in a variety of contexts including athletics, dance, medical, and aviation education.

In athletics, some report the ability to “see” with the “mind’s eye;” referring to “seeing” a movement (Morris, Spittle, & Watt, 2005). Conceptually, viewing images as “pictures” of the mind possess quasi-sensations which are experienced, evaluated, reacted to, and committed to memory similar to any other perceptual event. As illustrated by Posner (1978) and Hubel and Wiesel (1977), there are levels of equivalence between VI and perception. Specifically, Posner (1978) initially used a series of letter-matching studies to measure the mental processing time of several tasks (i.e., physical match, name match, and rule match) associated with the recognition of a pair of letters. Using the subtraction method, the time it took for participants to perform each cognitive process was associated with each physical task, indicating that high levels of the visual system are significantly influenced by one’s knowledge about objects and expectations. In contrast, lower visual levels are determined by the structure and function of the processing mechanisms (Marr, 1976). Since visual perception involves the activation of information processing mechanisms at many levels of the visual system, it is proposed that imagery also involves these same visual neural patterns.

Neuroscience researchers have found that many of the same neural patterns activated during visual perception are also found to be activated in VI (Farah, 1988; Finke, 1989; Kosslyn, 1994). Specifically, the middle occipital gyrus (Platel et al., 1997), middle temporal gyrus (Deutschlander et al., 2002; Rizzolatti et al., 1996), inferior occipital gyrus (Platel et al., 1997), posterior inferior temporal gyrus and fusiform gyrus (Deutschlander et al., 2002), supramarginal gyrus (Dupont, Orban, de Bruyn, Verbruggen, & Mortelmans, 1994), and inferior temporal gyrus (Kosslyn et al., 1994; Sergetn, Ohta, & MacDonald, 1992) showed activation in studies focusing on visual imagery and visual processing that instructed individuals to reconstruct mental images without direct visual stimuli.

Research involving neuroimaging techniques (i.e., PET and fMRI) typically examine similarities between brain activity of perception and VI while participants perform different VI tasks, showing deficits in imagery that are equivalent to visual neural pattern deficits in brain areas previously discussed (Farah, 1988; Kosslyn, 1994; Kosslyn & Koenig, 1995). However, it has also been shown by Behrmann, Winocur, and Moscovitch (1992) and Jankowiak, Kinsbourne, Shalev, and Bachman (1992) that patients who have disrupted perception can retain undamaged imagery processes to some extent. Although this is counterintuitive to imagery being equivalent to visual perception, these findings inform on the practical significance of imagery in rehabilitative contexts. Additional research examining normal patients has shown that nearly 65% of all brain areas activated between VI and visual perception are the same (Farah, Peronnet, Gonon, & Girard, 1988; Kosslyn et al., 2002, 1997; Kosslyn & Thompson, 2003; Mellet, Petit, Mazoyer, Denis, & Tzourio, 1998). Overall, Kosslyn (2005) concluded that the "bulk of evidence supports the claim that VI not only draws on many of the same mechanisms of visual perception, but also that topographically organized early visual areas play a functional role in imagery" (p. 342).

Although VI is important for learning and refining skills in a variety of contexts, KI is also involved in motor skill learning. Referring to internal and external information from receptors throughout the body, KI pertains to a sensory experience regarding body-part location and movement, the nature of objects coming into contact with the body, and the specific movements of the body (Schmidt & Wrisberg, 2004). Callow and Waters (2005) contend that KI involves the sensation of how a movement feels when performing an action, including force, effort, balance, spatial location, and movement time. The sensations that an individual experiences can either pertain to a body part or a piece of equipment that is being manipulated. For example, an individual could be asked to perceive the bodily sensation of a finger tapping sequence or the force of fingers pushing a basketball while dribbling without producing any movement. In the literature, however, KI has been difficult to separate from IVI, which is considered to contain a large kinesthetic component (McAvinue & Robertson, 2008).

Support for the independence of the kinesthetic modality is apparent from several studies in the physiology, psychophysiology, and cognitive brain research. Early EEG research completed by Davidson and Schwartz (1977) examined the pattern of occipital and sensorimotor activation of 20 right-handed female participants during self-generated VI and KI of three tasks (i.e., flashing light, tapping sensation on the right forearm, and both the light and tapping together). EEG was recorded from the left occipital and left sensorimotor regions showing that the visual task elicited greater visual neural patterns and the movement task elicited greater motor neural patterns, while the combined condition equally activated both areas. The difference between visual and kinesthetic imagery suggests that different imagery modalities elicit specific changes in the brain regions responsible for processing information in the relevant modalities (Davidson & Schwartz, 1977). However, this study may have been a result of alternate accounts: eye movements causing artifacts in the data, participants altering their performance to comply with the hypothesis of the experimenter, and task-induced demand characteristics (Berger & Gaunitz, 1979; Finke, 1985).

More recently, Guillot, Collet, and Dittmar (2004) also investigated the relationship between visual and kinesthetic imagery for a complex motor skill. Ten gymnasts (five females and five males) and 10 tennis players (five females and five males) completed embedded figure tests as well as a MI experiment that asked them to imagine a series of complex skills. Data involving mean group embedded figure test scores and skin conductance (i.e., skin resistance response patterns) indicated that gymnasts were equally able to perform visual and kinesthetic imagery, while the tennis players showed a more effective pattern only for VI (n = 5) or KI (n = 5). These results were supported by Farahat, Ille, and Thon (2004) indicating that MI may be relatively dependent on task requirements, which elicit changes in the brain that are responsible for processing information in the relevant modality.

Subsequent work by Neuper et al. (2005) compared EEG patterns of 14 right-handed participants during four different conditions involving a hand movement: KI, VI, motor execution and observation. Results indicated that EEG activity during motor execution and observation mapped onto appropriate areas with 80% accuracy and that the accuracy during KI was stronger (67%) than during the VI condition (57%). A subsequent study explored the changes in corticomotor excitability during kinesthetic and visual imagery of the same motor task (i.e., hand movement) in which 10 right-handed participants (six females and four males) completed a TMS experiment and 10 right-handed participants (seven females and three males) participated in an F-wave (applying a strong electrical stimulus to the skin surface to stimulate nerve impulses) experiment during four experimental conditions (rest, VI, MI, and KI) (Stinear, Byblow, Steyvers, Levin, & Swinnen, 2006). Findings indicated that KI and VI strategies have different effects on corticospinal excitability with KI being the only modality found to modulate the corticospinal excitability, including muscle-specific and temporally modulated facilitation, further supporting neurological differentiation between KI and VI.

Contradictory results, highlighting the inability to determine which imagery modality is being used based on corticospinal excitability, were found in a subsequent TMS study by Fourkas, Ionta, and Aglioti (2006) who examined the corticospinal excitability during MI of a thumb-palm opposition movement. Surface electrodes were placed over the opponens pollicis and abductor digiti minimi on the right hand of 13 healthy participants (five females and eight males), and focal TMS was performed over the left M1 during four motor imagery blocks (two KI and two VI). Results of paired *t*-tests indicated no overall difference between imagery modality, suggesting that the effects of VI and KI are similar. In addition, Taktek, Zinsser, and St-John (2008) attempted to determine the modality that is most efficient for the retention and transfer of a closed motor skill. Right-handed male and female participants (n = 96) completed a French version of the VMIQ (Fournier, le Cren, Monnier, & Halliwell, 1994) before being divided into two groups (boys and girls) that ranged from good imagers to poor imagers, for each group, based on their imagery ability score. Participants were further divided into six experimental groups (VI combined with physical practice, KI combined with physical practice, EVI, IVI, KI, and specific physical practice) composed of eight girls and eight boys to maintain a homogenous imagery ability between the groups, and then were asked to complete an underarm throw of a ball toward a target. Overall, KI and VI did not allow for the achievement of equivalent or superior results to those in the specific physical practice group during the initial trials; however, equivalent results were produced between all experimental groups from pre-test to post-test and retention phases. These results fail to show any differences between visual and kinesthetic imagery conditions, indicating that one modality may not be superior to the other and that they may be neurologically similar. Possible explanations offered for these equivocal findings include: not controlling for imagery ability at pre-test (e.g., holding imagery ability of the participants constant as a covariate), task unfamiliarity

(Hardy & Callow, 1999), the modality of an image being less important than its purpose (Fourkas et al., 2006), and the similarity of behavioral, central and peripheral evidences shared by mental and physical practice (Holmes & Collins, 2001).

Examinations of the specialized neural systems activated during visual and kinesthetic imagery modalities are rare. Guillot et al. (2009) directly compared brain activity during visual and kinesthetic imagery of 13 volunteers (seven females and six males), rated as good to excellent imagers (as defined by at least one standard deviation above a mean global imagery score: ANS score, MIQ-R score, auto-estimation score, and MC score), completing a finger sequence task in four conditions (physical execution, VI, KI, and perceptual control). Results showed the involvement of the primary visual area, prestriate cortex, and visual pathways (i.e., superior parietal structures and precuneus) during VI, confirming the neuroactivity accuracy results during VI of previous neuroimaging studies (Jackson, Lafleur, Malouin, Richards, & Doyon, 2000; Mellet et al., 1998; Solodkin, Hlustik, Chen, & Small, 2004; Thompson & Kosslyn, 2000; Zacks, Ollinger, Sheridan, & Tversky, 2002). In addition, only KI was found to bilaterally activate the inferior parietal lobe, which is crucial for MI (Decety et al., 1994; Gerardin et al., 2000; Nair, Purcott, Fuchs, Steinberg, & Kelso, 2003; Stephan et al., 1995; Suchan et al., 2002). Findings from Guillot et al.'s (2009) study point to different neural processing in VI compared to KI conditions. Specifically, VI has increased visual neural patterns in the brain areas responsible for generating mental images and KI corresponds to increased activity in the motor neural areas that produce movement. In studies like this, it is important to control participant compliance to instructions because it is often difficult to dissociate VI from KI. However, this study is limited by only using good imagers, selected using a global imagery score [(ANS score + MIQ-R score + auto estimation score) – (MC score)] as well as varying task difficulty, causing participants to rely less on motor simulation than on memory retrieval.

Gabbard, Ammar, and Cordova (2009) tested the distinctiveness of VI and MI in an interference tactic research paradigm to explore if the two imagery modes possess distinctive processing properties. Twenty-nine right-handed male and female participants completed two reaching tasks in both imagery conditions. Greater accuracy in MI compared to VI for judgments of estimation was found, as well as significant differences in total error data in which participants engaging in MI committed fewer errors. Additional support for modality distinction comes from Stecklow, Infantosi, and Cagy (2010) who investigated the changes in EEG alpha power during sequences of visual and kinesthetic MI. EEG signals of the occipital and parietal regions were acquired from 15 elite volleyball players and 18 novices (no volleyball experience) during sequences of MI of a volleyball spike in kinesthetic or visual modalities. Results indicated that there were significant differences between modalities, where KI was significantly stronger than VI, with athletes more easily imaging than non-athletes. Furthermore, Giron, McIsaac, and Nilsen (2012) compared the effects of EVI and KI on pelvis and hip kinematics during two dance movements, plié and sauté, in a pilot study. Three female dancers were assigned to one of three groups (VI, KI, or no imagery). Peak external hip rotation varied in both modality and task, indicating that different imagery modalities are task specific by comparing the effects of VI and KI.

With the evolution of this research, it is becoming apparent that neurophysiological data support the distinction between VI and KI, thus, indicating that VI activates visual neural pathways and KI activates motor neural pathways (Annett, 1996; Berthoz, 1996; Decety, 1996; Farah, 1989; Holmes & Collins, 2001). However, most of these studies did not account for imagery ability which is a key component of MI, where those with higher imagery ability are believed to benefit more from using imagery compared to those with lower imagery ability. In studies where participants were selected and/or separated based on imagery ability, it was done using a composite score of the conditions on a self-report imagery questionnaire or another composite score using multiple measurement techniques (i.e., global imagery score). This is a major flaw of measuring imagery ability in these studies, especially using a composite score because the questionnaires (i.e., MIQ-3 and VMIQ-2) are formatted to measure each modality and perspective separately. The combination of all imagery conditions in a single score contradicts the sensitivity of capturing perspective and modality differences the questionnaires were designed to measure; consequently, the ability to effectively separate good imagers from poor imagers is diminished.

Imagery Ability

Imagery ability is generally described as an individual's capacity to form and control images that are created, as well as how vivid and realistic these representations of movements are, in the sense that they can describe the characteristics of the motor task (Guillot & Collet, 2005; Martin, Moritz, & Hall, 1999). According to Paivio (1985) imagery is an ability that improves with practice where those with a higher capacity to generate images are proposed to benefit more from mental practice efforts. Further, imagery ability is a product of experience and genetic variability with the latter being the limiting factor of its effectiveness. Originally hypothesized by Paivio (1985), some variations in imagery ability are attributed to brain differences. At the time, however, the difference in imagery ability as a result of variability in the brain was nothing more than speculation given that no empirical evidence was provided to support this claim. In the cognitive neuroscience literature of that time, imagery was proposed to have a role in memory (Paivio, 1985) and research paradigms were predominantly behavioral experiments involving electrophysiological measurements (see Farah, 1988; Farah, Peronnet, Gonon, & Giard, 1988; Farah, Weisberg, Monheit, & Peronnet, 1989). With the advent of brain imaging techniques in the 1980s (i.e., PET, fMRI) converging evidence continued to indicate that brain differences separated good and poor imagery abilities (Kosslyn, 1996; Kosslyn, Margolis, Barrett, Goldknopf, & Daly, 1990).

Findings in cognitive neuroscience note that imagery ability is one of the most variable moderating factors of neural activity and that it is a more complex topic that goes beyond the vividness of an image (Guillot et al., 2008). Imagery ability has been shown to distinguish between successful and less successful performance (Murphy, 1994), as well as impact the effectiveness of an imagery intervention (Hall, Buckolz, & Fishburne, 1992). For example, Goss, Hall, Buckolz, and Fishburne (1986) examined the relationship between imagery ability and the acquisition, retention, and reacquisition of movements. Thirty participants completed four movement patterns after being separated into the following imagery groups as measured by the MIQ: good visual/good kinesthetic (n = 10), good visual/poor kinesthetic (n = 10), and poor visual/poor kinesthetic (n = 10). Results for the acquisition and reacquisition of movements showed that the good visual/good kinesthetic group acquired the movements in the least number of trials, while the poor visual/poor kinesthetic required the greatest number of trials. A similar study by Robin et al. (2007) examined how imagery ability affected motor improvement on tennis service return accuracy of 80 skilled tennis players who were divided into three groups according to their MIQ scores (good imager, poor imager, and control group). Absolute and variable error analyses were used to compare pre- and post-test performance of service returns showing that good imagers performed significantly better than poor imagers for amplitude and accuracy. Both of these studies indicate that good imagery ability impacts MI practice on motor performance, especially facilitating the acquisition of movements.

In a related study, Lawrence, Callow, and Roberts (2013) explored the role of imagery ability in the effectiveness of observationally learning a gymnastics floor routine of 40 participants assigned to one of four groups (i.e., good imagery ability and observational learning, poor imagery ability and observational learning, good imagery ability control, and poor imagery ability control). A significant experimental phase x group interaction was found ($F_{(3, 36)} = 56.62$, $p < 0.001$, $\eta_p^2 = 0.83$). Specifically, the good imagery ability and observational learning group (Mean = 6.22 ± 1.71) performed significantly better than the poor imagery ability and observational learning group (Mean = 4.48 ± 1.65). This suggests that imagery ability moderates the effectiveness of observational learning on acquiring a motor sequence, which may be caused by an increase in brain activation in areas (e.g., SMA) important for movement pattern acquisition.

Two dimensions of evaluating the quality of an image include vividness and controllability (Denis, 1985; Gould & Damarjian, 1996; Lequerica, Rapport, Axelrod, Telmet, & Whitman, 2002). An individual's capacity to form these types of images (i.e., good or poor imagery ability) is inferred from both subjective and objective measures. Subjective reports of imagery vividness are one of the most frequently examined aspects of imagery ability (Cui, Jeter, Yang, Montague, & Eagleman, 2007; Deschaumes-Molinaro, Dittmar, & Vernet-Maury, 1991; Hishitani & Murakami, 1992). Vividness refers to how clear and real an image appears (Roberts, Callow, Hardy, Markland, & Bringer, 2008). In addition, vividness is thought to be related to the level of interest, meaningfulness, and affect associated with the image generated (Kaufman, 1981). In other words, vivid MI should consist of mental representations using detailed sensory cues, typically those from previous perceptual experiences. Findings from sport psychology support this idea by examining how to improve sport performance, showing that both physical practice and imagery groups equally improve significantly compared to control groups (Holmes & Collins, 2001; Wakefield & Smith, 2012). The vividness of an image is important in order to create or re-create the actual experience within an individual's mind. Specifically, effective images (i.e., ones more likely to produce real-life experiences) are said to include several key components (i.e., physical, environment, task, timing, learning, emotion, and perspective) (Holmes & Collins, 2001). In order to produce effective images, an individual has to be able to generate and continually inspect the vividness of the image he or she produces.

Controllability, another important feature of imagery ability, refers to the ease and accuracy that image content can be manipulated and transformed (Guillot & Collet, 2010; Moran, 1993; Roberts et al., 2008). Having control of an image allows for its maintenance over a certain period of time (Denis, 1985) and provides an individual the capacity to influence the image content (Murphy, 1994). This dimension is important in understanding one's imagery ability in the physical and sport contexts, particularly when participants have to mentally rotate a perceptual stimulus or manipulate an object in space (i.e., ball juggling in soccer, body rotation in gymnastics, and stroke rehabilitation). Proficiency in the ability to control one's image facilitates the individual's ability to visualize the intended accomplishments or goal of the task, instead of making possible errors. To illustrate this, 50 male college students were randomly assigned to an experimental condition that either imaged or did not image the physical movements associated in successfully completing a golf putt (Cho, 2009). Participants in the imagery groups were provided with standard images to use and then asked to complete an imagery questionnaire after each image. Results showed that participants who were able to control the outcome of an image prior to performing that activity had greater influence on subsequent performance than did imagery of the motor movements that make up-the task itself.

In addition, literature reviews indicate that differences in the characteristics that an individual uses when mentally practicing a task can influence the transferability to actual performance of other tasks (see Robertson, 2002). This was examined in a neuroscience study involving 16 right-handed males completing two mental rotation tasks, one involving an object and the other a hand (Wraga et al., 2003). Utilizing PET rCBF was found to be greater in the mental rotation hand task in the pre-motor and primary motor areas of the brain. It was concluded that motor activation from an imagined hand rotation task can be transferred to other mental rotation tasks, and that a participant's ability to transform objects in their mind similarly to physical practice may be related to mental rotation being an incremental process. These studies illustrate that the closer the image is to the real performance, in terms of vividness and controllability, the easier it will be to transfer the skill correctly.

Evidence regarding imagery ability indicates that even though individuals can be categorized by self-report questionnaires as vivid imagers, if they do not have control of their image their overall performance can still be poor (Epstein, 1980). Isaac (1992) conducted a study to test the hypothesis that individuals who produce better images and have control over them will elicit better performance. Novice and experienced trampolinists (n = 78) identified as good or poor imagers were randomly assigned to an experimental (i.e., mental practice) or a control condition and completed a six-week training period. Post-training performance measures presented a significant difference between good and poor imagers with good imagers improving more than poor imagers. This also illustrates that there is a link between an individual's imagery ability assessed by self-report questionnaires and their physical performance. In addition, MacIntyre, Moran, and Jennings (2002) investigated the relationship between imagery (i.e., controllability) with canoe-slalom performance in elite (n = 19) and intermediate (n = 12) athletes. It was reported that canoe-slalom performance can be predicted using an objective imagery ability measure (i.e., mental rotation test) between elite and intermediate athletes. In a series of studies examining performance (i.e., flexibility and learning a forearm pass in volleyball) and self-reported imagery ability, performance gains were found between the experimental groups and a control group after completing a training program (Ay, Halaweh, & Al-Taieb, 2013; Guillot, Tolleron, & Collet, 2010). Overall, studies examining vividness and controllability conclude that individuals who self-report more vividness and are able to control these images will further benefit from imagery interventions. What remains unknown is if these results are directly related to imagery or confounded by other factors (e.g., better technical execution, improved information processing), and if objective measures (i.e., fMRI) can support a direct link between participant variability self-report imagery ability and performance.

In an attempt to increase our understanding and expand imagery research, the functional equivalence and simulation theories extend the common theoretical underpinnings of imagery by incorporating cognitive neuroscience research in an attempt to increase our understanding of how to measure imagery ability. In a study by Roure et al. (1999) performance improvement with imagery quality estimated during ANS recording (i.e., skin potential and resistance, skin blood flow and skin temperature, and instantaneous heart rate and respiratory frequency) of volleyball training (“receiving serve”) was evaluated from the accuracy of a pass to a targeted teammate.

Pre- and post-tests were completed on 12 participants (gender not indicated) separated into two groups (imagers and controls), according to self-reported imagery ability scores (i.e., MIQ), to measure real-time monitoring during imagery sessions. Correlations between imagery quality and performance showed that performance was strongly correlated with ANS response ($r = 0.79$, $p = 0.0019$). Furthermore, this correlation between participants with a “high” (grade = +20) and a “poor” (grade = -4) ANS response and performance improvement suggests that an objective evaluation of an individual’s imagery ability can be obtained.

Most recently, van der Meulen, Allali, Rieger, Assal, and Vuilleumier (2012) investigated imagery ability differences on the correlates of gait control with 20 healthy participants separated into two groups (good and poor imagers) based on their performance on two MC tests. Using fMRI, three different tasks (MI, VI, and control) were able to identify good imagers from poor imagers; good imagers showing increased activation in the right M1, left prefrontal cortex, right thalamus, and bilateral cerebellum compared to poor imagers. Although the capacity for good imagers to recruit motor areas during MI was found, the two groups (i.e., good and poor imagers) did not differ on vividness ratings of an imagery ability questionnaire suggesting that self-report questionnaires may not be a valid method to measure imagery ability. However, the task used did not only involve gait, it also required participants to complete other cognitive functions (i.e., goal-directed behavior, spatial orientation, and time estimation) which may have caused less cortical and more subcortical, brainstem and cerebellar activation (Jahn et al., 2008). Although van der Meulen et al. (2012) were able to demonstrate better gait control among good imagers as classified by MC, imagery ability scores did not correctly classify IA groups. Therefore, future studies should continue to examine validated imagery ability questionnaires and their capability to separate participants into good and poor imager groups.

Despite the emerging neuroscience evidence in support of imagery, respective neurological convergent validity evidence supporting common imagery ability assessments is necessary to establish the efficacy of using these self-report instruments. This is important because it is common for researchers to measure imagery ability as inclusion criteria (see Collet, Guillot, Lebon, MacIntyre, & Moran, 2011; Guillot & Collet, 2010; Guillot et al., 2008, 2009; Lebon, Byblow, Collet, Guillot, & Stinear, 2012; Roure et al., 1999; van der Meulen et al., 2012) or as a means of separating participants in to experimental groups when testing the effectiveness of imagery interventions focused on varying mode or perspective (see Cho; 2009; Cumming & Ramsey, 2008; Rodgers, Hall, & Buckolz, 1991 Roure et al., 1999). Although a substantial amount of literature in both sport and neuroscience has increased our understanding of how MI differs from actual physical movement and what brain areas are activated during MI and ME (see Table 1.1), imagery remains a complex, internal experience, which can never be explicitly measured. The body of imagery literature and thereby practice, stand to benefit from more systematic inquiry determining if, and to what extent neurological activity converges with self-reported imagery ability characteristics as measured when participants are instructed to engage in specific modes and perspectives. To this end, self-report imagery ability measures will be discussed next.

Measurement of Motor Imagery Ability

Measuring motor imagery continues to be an area of focus across many fields (i.e., sport psychology, physical education, and neuropsychology), with most studies relying on various subjective, self-report, and objective measures. Initially, Hall et al. (1985) reviewed data examining imagery ability to determine the appropriate tests to measure individual differences revealing: (1) subjective and objective measures tend to be uncorrelated and, thus, do not measure the same underlying ability, (2) there is limited support for the relationship between imagery ability and motor skill performance, and (3) that tests have not been specifically designed to measure imagery of movement. In order to target these limitations, self-report questionnaires were developed to show consistent relationships of measuring visual and kinesthetic movement imagery. The bulk of what is known about imagery measurement, especially in the sport science literature, rests on various psychometric iterations of two self-report inventories: the MIQ and VMIQ. Through psychometric validation processes the VMIQ-2 (Roberts et al., 2008) and MIQ-3 (Williams et al., 2012) are the most current versions available, both offering an efficient way of measuring imagery ability using three subscales (EVI, IVI, and KI) confirmed in factor analyses. Interestingly, these questionnaires have been adopted in neuroscience for screening purposes (e.g., Guillot et al., 2009) and testing intervention effects (Guillot et al., 2008; Roure et al., 1999), but still cannot be used interchangeably because the possibility of potential flaws and erroneous findings (Lequerica et al., 2002).

To this end, the utility of novel motor imagery indexes have been established using a combination of qualitative, psychometric, chronometric, and psychophysiological approaches to more accurately measure MI ability. However, the fundamental limitation of these rests on incorporating the VMIQ and MIQ because it is not currently known to what extent blood oxygenation reflects different types of mode/perspective specific to imagery ability. Despite the use of objective measures in neuroscience, it is currently unknown if these measures support the construct validity of the self-report imagery ability measures, which is essential to inform researchers about for the efficacy and continued use of the MIQ-3 and VMIQ-2. If self-report measures can correctly screen imagery ability then areas of the brain that are thought to be active during visual or kinesthetic imagery should be more active while individuals engage in the respective imagery mode to provide convergent validity between like scales as well as discriminant validity between different scales.

The following sections will review the methods utilized for measuring imagery ability, considering the associated findings, psychometric properties, and limitations. First, subjective methods of measuring imagery ability will be discussed, including mental chronometry and self-report imagery questionnaires (i.e., MIQ and VMIQ), followed by an in-depth analysis of objective measurements (i.e., TMS, PET, and fMRI) used in the neuroscience literature.

Subjective Measures

Mental chronometry. Mental chronometry is the measurement of cognitive speed, or the actual time taken to process information of different types and degrees of complexity. The basic measurement for chronometric studies is response time, represented as the minutes and seconds, to a stimulus that calls for a decision to be made by an individual. Having response time as the unit of measure may be confusing given the unit of measure but despite being quantifiable, response times are based on the subjective decision to stop a timer or report the number of times a movement was imaged compared to physical execution in a given time period. Mental chronometry measures imply imagery ability to control or manipulate an image and have been routinely utilized with visuospatial tasks such as mental rotation (Lequerica et al., 2002). These chronometric, or "time-measuring," studies provide more accurate information of imagery than can be obtained with simple questionnaires by allowing researchers to ask individuals what information is and is not prominent in an image (i.e., image-scanning task). Studies using MC link performance to cognitive ability include: participants recalling if a number was in the previous set of digits or not (Sternberg, 1966), determining whether a pair of three-dimensional shapes was identical or mirror-image versions (Shepard & Metzler, 1971), and identifying whether two letters were the same or not (Posner, 1978). This information can be used as a basis for asking how "picture-like" images are (Reisberg, 2006), which can also be transferred to the motor domain in asking how "performance-like" images are. The accuracy and speed of responses as measured in chronometric studies infer hypotheses concerning the vividness, controllability, and exactness of reference of imagery (Reisberg, 2006). From a practical standpoint, when learners in movement contexts engage in mentally rehearsing a motor skill sequence in real-time speed, evidence suggests psychoneuromuscular pathways strengthen and enhance physical performance (O & Hall, 2009).

Researchers have realized that the speed at which an individual images is closely linked to actual ME (Nideffer, 1985), which follow the biomechanical constraints of the movement (Johnson, 2000). The use of real-time speed of imagery was highlighted by Holmes and Collins (2001), but image-speed interventions using different speeds have also been administered to examine learning/practicing motor skills (Louis, Guillot, Maton, Doyon, & Collet, 2008; O & Munroe-Chandler, 2008). In two experiments, Louis et al., (2008) examined the effect of imagined movement speed on subsequent motor performance over a training period. In experiment one, 24 student participants (15 males and nine females; Mean age = 27.2 ± 3.6 years) were separated into three groups (i.e., fast, slow, and control) and completed the MIQ-R followed by imaging two series of body movements (i.e., upper body and lower body, each with seven different steps) using IVI in a three week training protocol. Participants' imagery ability assessment indicated no significant differences between group (fast = 44.3 ± 6.4; slow = 44.6 ± 5.13; control = 44.4 ± 4.7, $p > 0.05$), gender (males = 42.8 ± 4.2; females = 45.4 ± 5.7, $p > 0.05$), or imagery condition (fast VI = 22.6 ± 3.1 and fast KI = 21.6 ± 4.2; slow VI = 24.6 ± 3.5 and slow KI = 20 ± 3.6; control VI = 24.3 ± 2.6 and control KI = 20.2 ± 3.1, $p > 0.05$). The effect of imagined movement speed for both upper body and lower body sequences revealed a significant difference in the fast MI group for sequence time (upper body: pre-test = 7.49 ± 2.2 s and post-test = 6.95 ± 2.4 s; lower body: pre-test = 5.54 ± 1.3 s and post-test = 5.52 ± 1.91 s, $p < 0.01$), but not in the slow MI group (upper body: pre-test = 13.46 ± 3.5 s and post-test = 8.70 ± 3.60 s; lower body: pre-test = 10.13 ± 2.1 s and post-test = 6.51 ± 2.22 s) or the control group (upper body: pre-test = 10.29 ± 2.4 s and post-test = 10.21 ± 2.91 s; lower body: pre-test = 7.27 ± 1.3 s and post-test = 7.57 ± 2.18 s) ($p > 0.05$) indicating a change in participants' ME duration when increasing the speed of imagery. Experiment two participants included 21 skilled athletes (12 males and nine females; Mean age = 16 ± 0.25 years) that completed the same procedure as experiment one over a four-week period using a judoka movement. Participants' imagery ability assessment indicated no significant differences between group (fast = 46.6 ± 9.5; slow = 41.7 ± 5.75; control = 43.6 ± 6.99), gender (males = 45.3 ± 7.76; females = 42 ± 7.35), or imagery condition (fast VI = 23.6 ±5.4 and fast KI = 23 ± 4.7; slow VI = 21.4 ± 2.7 and slow KI = 20.5 ± 3.6; control VI = 22.8 ± 2.4 and control KI = 20.4 ± 4.2, $p > 0.05$). When examining movement times, all movement durations were significantly different (fast: pre-test = 37.3 ± 1.2 s and post-test = 34 ± 1.5 s; slow: pre-test: 42.4 ± 0.9 s and post-test = 48.9 ± 1.0 s; control: pre-test = 40.5 ± 1.6 s and post-test = 39.2 ± 0.45 s, $p < 0.001$), with the fast MI group's time shorter in duration, the control group's time decreasing slightly and the slow MI group's time increasing from pre-test to post-test. When comparing the physical completion of the task with each imagery condition it was shown that changing MI speed can modify the actual speed of well-learned motor tasks. Overall, both experiments indicate that voluntary increases in MI speed increases the actual speed of ME, while decreases in MI speed slows ME.

Studies by O and colleagues (2008, 2009) further examined the effect of speed on the performance of a soccer task, as well as the intentional use of slow motion, real-time and fast motion images. For example, a sample of 97 university-aged participants (32 males and 65 females; Mean age = 18.1 ± 1.88) completed the MIQ-R and were separated into three imagery practice conditions (i.e., real-time, slow motion, slow motion concluded with real-time), a physical practice condition, or a control condition to examine the performance of a soccer dribbling task over seven trials (O & Munroe-Chandler, 2008). Results revealed that the MIQ-R scores of the five groups did not significantly differ (visual = 23.36 ± 3.43; kinesthetic = 21.79 ± 4.50, $p > 0.05$), but the intervention resulted in significantly decreased performance times ($p < 0.01$ for all groups) and significantly improved error performance ($p < 0.01$ for all groups except the control condition) from pre- to post-intervention. Findings indicate that image speed did not have an effect on subsequent soccer dribbling performance which is contradictory to the aforementioned Louis et al. (2008) study.

In addition, O and Hall (2009) quantitatively analyzed athlete’s voluntary use of slow motion, real-time and fast motion images, as well as the influence of gender and competitive level on reported voluntary image speed use. Participants included 604 athletes (298 males and 306 females; Mean age = 21.73 ± 4.54 years) that completed the image speed questionnaire (ISQ) which assesses athlete’s relative use of voluntary slow motion, real-time, and fast motion images. Within-ISQ item analyses for gender indicated that females reported employing significantly more slow motion images than males ($F(1, 519) = 10.56$, $p = 0.001$, $\eta^2 = 0.02$) and males reported using significantly more real-time ($F(1, 519) = 3.99$, $p = 0.005$, $\eta^2 = 0.01$) and fast motion ($F(1, 519) = 5.31$, $p = 0.002$, $\eta^2 = 0.01$) images than females, while the competitive level analyses had no significant effect on reported image speed use ($p > 0.006$ for all). Between-ISQ item analyses for both gender ($p > 0.02$) and competitive level ($p > 0.02$) failed to reveal a significant effect on athletes reported use of different imagery speeds. Overall, athletes were found to utilize all three image speeds to varying degrees depending on the function of imagery being employed. Specifically, real-time images were used most often regardless of the function or stage of learning, while slow motion images were most often used when learning or developing a skill/strategy and fast motion images were most often used for imaging skills/strategies that had been mastered. Overall, the speed at which one images can affect the timing of physically executing the same task and should be considered when examining the effect of MI on performance, especially within MC paradigms.

The use of MC paradigms indicates that the duration of an imagined movement is similar to the time required to physically perform it (Bakker et al., 2008; Calmels, Lopez, Holmes, & Namen, 2006; Guillot & Collet, 2005; Jeannerod, 1997). Bakker et al. (2008) used MC during fMRI scanning to examine whether imagery time conformed to Fitts's Law for each task (i.e., walking a broad path or walking a narrow path). Results showed that a narrower path resulted in longer imagery times during the MI task, $F(1, 14) = 37.0$, $p < 0.001$. Not only did this study further confirm the inverse relationship between movement difficulty and imagined movement times, it demonstrated that an fMRI environment may not affect results obtained during MI procedures because the inverse relationship observed with the physical task continued to be present during the MI task. Furthermore, task difficulty and stability to image affects both the actual and imagined amount of time necessary to complete a task (Decety, 1991; Decety & Jeannerod, 1996). Studies have supported Fitts's Law (Fitts & Posner, 1967; Fitts, 1954) showing that a linear relationship exists between response time for a correct response and the degree of task complexity; consequently, supporting the notion that more difficult tasks take more time to execute than easier ones even with MI (Decety, 1991; Decety & Jeannerod, 1996; Maruff et al., 1999). From this information, it can be implied that individuals who take longer to physically perform the same, especially simple tasks, have poor imagery ability (Hall, et al., 1985).

Lequerica et al. (2002) reasoned that MC data could also provide a means of construct validity for self-report imagery questionnaires. Although imagined and actual movement times are considered to be similar, participants are still required to subjectively report image frequency or stop a timer once the image is completed to compare actual and imagined movement times and infer imagery ability. Although such comparisons provide important information about an individual's imagery experience, this paradigm does not provide information about an individual's capacity to form vivid and accurate images (Guillot & Collet, 2010). Since MI is considered a personal experience, with only the individual knowing what is actually being imaged, equating the results from these measures to their imagery ability may be inappropriate given that several other methods (i.e., social desirability, response bias) may be used to complete the task (Richardson, 1977). In addition, the interpretation of mental chronometric measures are not always straightforward because several extraneous factors need to be considered (i.e., temporal constraints, movement experience, gender, and level of arousal) before drawing a conclusion about imagery ability. Because of these limitations, accounting for mental chronometric measures concurrently with other imagery measures is an important study design feature when embarking on validating movement imagery assessments.

Self-report questionnaires. Psychometrically validated self-report questionnaires designed to measure individual differences in imagery content and function (i.e., motivation, practicing skills, and arousal control) and ability (i.e., ease of generating an image, vividness, and controllability) (Moran, 1993) remain prominent in the sport sciences. The choice of which questionnaire to use should be based on the study population, the purpose of the questionnaire and study, practical considerations (e.g., ease of scoring and data collection efficiency), and its psychometric properties. Both vividness and ease of generating an image have been used to examine the use of MI in relation to performance (MacIntyre & Moran, 1996), the effect of MI on learning sports skills (Roure et al., 1999), and the controllability of an image using mental rotation tests (Vandenberg & Kuse, 1978), all indicating better performance on tasks when having good imagery ability. However, because it is difficult to create tasks that objectively assess imagery ability of movements, self-report measures of imagery vividness and controllability are commonly used in the measurement of MI ability (i.e., VMIQ-2: Roberts, Callow, Hardy, Markland, & Bringer, 2008; MIQ-3: Williams, Cumming, & Edwards, 2011). Unfortunately, few studies exist examining the psychometric qualities of these questionnaires, and even less studies geared at validation in conjunction with contemporary objective measures (i.e., fMRI, PET, and EEG).

Establishing the psychometric properties, especially convergent and discriminant validity, is essential to the structure of instruments and procedures for measurement and the development and refinement of theoretical approaches to measuring imagery and its dimensions. Convergent validity (using two different measurements and research methods (i.e., self-report questionnaire and fMRI) to collect data concerning construct and discriminant validity (demonstrating that the construct (i.e., imagery) is different from others that may be present (i.e., rehearsal or modeling)) are ways to help establish construct validity (Campbell & Fiske, 1959). Often times, concurrent validity (correlating a new measure with a "gold standard" at the same time) is used interchangeably with convergent validity, but what convergent validity emphasizes that concurrent validity does not, is using different measurement methods that are linked by theory.

Self-report questionnaires require participants to engage in a task and rate their imagery experience on a Likert scale. This type of scale is ordinal in nature causing the distance between two scores to be unequal, which may limit individual differences or similarities. This plays a role in how the information from self-report questionnaires is interpreted because what a participant may experience as easy or vivid may not be what another participant experiences who reports the same score for ease or vividness. Many of these questionnaires involve individuals imaging a specific movement and rating the ease or difficulty (e.g., MIQ: Hall et al., 1985) or vividness (VMIQ: Isaac, Marks & Russell, 1986) of generating that image. This process involves retrieving experiences from memory, with the degree of ability to image the movement being contingent on how often as well as how recently it might have been viewed.

Vividness of movement imagery questionnaire-2 (VMIQ-2). The VMIQ-2 is a frequently used instrument that involves vividness ratings of previously experienced movements; variability of when the movements were last performed (i.e., temporal experience with the movement) is highly variable. Originally developed as the VMIQ, this questionnaire was constructed to answer questions relating movement imagery to motor performance. Specifically, the vividness of visual and kinesthetic MI is assessed (McAvinue & Robertson, 2008) on a 24-item questionnaire; each item is a description of a common movement, from basic movements (e.g., walking) to those that are more demanding in nature (e.g., riding a bike or kicking a ball in the air). Participants are instructed to imagine each item, first with respect to somebody else completing the movement and then themselves completing the movement. After completing the task, individuals rate the vividness of the image on a 5-point Likert scale (5 = “no image at all, you only know that you are thinking of the skill” to 1 = “perfectly clear and as vivid as normal vision”) (Isaac, Marks, & Russell, 1986). The visual and kinesthetic modalities are captured by summing the scores of all of the items, ranging from 24-120 for each modality. Two limitations of the VMIQ are: 1) the counter intuitive scale anchors where a low score delineates better imagery ability, and 2) memory decay; time since experiencing the movements specified in each item may vary between participants confounding self-reports of imagery ability.

Despite the VMIQ being limited by memory decay, it was deemed reliable and stable by Isaac et al. (1986); the three-week test-retest reliability with a group of physical education students was acceptable (*r* = 0.76). In addition, it was found that there were no significant differences within the questionnaire when administered over a six-month time period, illustrating stability. The VMIQ also demonstrated adequate concurrent validity with the VVIQ with novice (*r* = 0.75), experienced (*r* = 0.45), and elite (*r* = 0.65) trampolinists, as well as a high positive correlation with the VVIQ (*r* = 0.81) indicating convergent validity (Isaac et al., 1986). Furthermore, Eton, Gilner, and Munz (1998) suggested that athletes could be differentiated on the basis of their VMIQ "self" (participants image themselves moving) scores. Eton et al.'s (1998) study also established good internal consistency (α = 0.97) and acceptable two-week test-retest reliability for the "self" scale (*r* = 0.80) but not for the "other" (when participants imagined somebody else moving) scale (*r* = 0.64).

Like all self-report questionnaires, the VMIQ is not without limitations. A main concern with the initial version of the questionnaire is its ability to differentiate KI from VI because participant instructions appeared to be vague. Furthermore, the directions of the first version did not delineate between using an internal or external imagery perspective; participant's perspective preference may have confounded scores.

In line with current conceptualizations of the internal and external imagery perspectives, the VMIQ was revised (Roberts et al., 2008). This revision captures three different imagery types; EVI was defined as third-person imagery of the self, IVI was defined as first-person VI, and KI was defined as imagery of the feel of the movement.

Participants rate each item of the three scales on a 5-point Likert scale where 1 = "perfectly clear, vivid image" and 5 = "no image at all." Scores are summed for each scale, range from 3 to 15, and represent a vividness subscale; counterintuitively, lower scores represent better imagery ability. Some researchers stipulate a three-scale composite scoring criteria of less than 72 as adequate imagery ability (Hardy & Callow, 1999; Smith & Holmes, 2004). However, the practice of composite scoring is also counterintuitive in that it negates contemporary conceptualization of imagery which the questionnaire was designed to capture.

In a psychometric validation study, Roberts et al. (2008) completed a multi-trait multi-method (MTMM) approach to confirmatory factor analysis (CFA) using a correlated traits/correlated uniqueness (CTCU) model to examine the factorial structure of the 24 item VMIQ-2. Results illustrated a three factor CTCU analysis performed on the 12 item questionnaire revealing an acceptable fit (Satorr-Bentler χ^2 (555) = 840.65, $p < 0.001$; RMSEA = 0.08, $p = 1.00$; CFI = 0.98; SRMR = 0.004, NNFI = 0.97, with factor loadings ranging from 0.60 to 0.78. According to the three factor CTCU analysis, the number of items on the VMIQ-2 was decreased from 24 to 12, in which IVI and KI should be treated as separated modalities.

Further psychometric analyses assessed the concurrent and construct validity of the VMIQ-2 (Roberts et al., 2008) in relation to another commonly used instrument, the revised Movement Imagery Questionnaire (MIQ-R: Hall & Martin, 1997). Internal consistency of the VMIQ-2 was high: EVI = 0.95, IVI = 0.95 and KI = 0.93. Concurrent validity analysis with the MIQ-R showed that both internal and external visual imagery factors of the VMIQ-2 were significantly correlated with the visual factor of the MIQ-R (IVI and VI, $r = -0.342$, $p < 0.05$ and EVI and VI, $r = -0.647$, $p < 0.01$), and the kinesthetic factors were both significantly correlated ($r = -0.736$, $p < 0.01$). In addition, construct validity was revealed by significant differences between good- and poor-level athletes for each variable: EVI, t (196) = -2.55, $p < 0.01$ $d = 0.36$; IVI, t (181.66) = -2.56, $p < 0.01$ $d = 0.36$; and KI, t (186.49) = -2.87, $p < 0.005$ $d = 0.40$. Overall it is evident that the VMIQ-2 is a valid measure as illustrated by a three-factor structure, concurrent validity, and construct validity. However, memory decay remains an inherent limitation tied to its retrospective movement experience protocol.

Movement imagery questionnaire-3 (MIQ-3). In contrast, the unique protocol of the MIQ accounts for memory decay, by including physical movement prior to engaging in an imagery task. The original MIQ (Hall, Pongrac, & Buckolz, 1985) was developed to address inconsistent results from inadequate measurements and equivocal findings questioning whether imagery ability influences performance gains. The original version of the MIQ consisted of 18 items that entailed physically performing nine movements (e.g., raising and lowering the right knee, performing a front roll on a mat and finishing in a standing position), then visually and kinesthetically imaging those movements before rating the ease or difficulty of generating those self-images on a seven-point Likert scale (1 = easy to 7 = difficult). Acceptable reliability as internal-consistency coefficients ranged from 0.87 to 0.89 (visual) and 0.86 to 0.91 (kinesthetic). Hall et al. (1985) also showed test-retest reliability of 0.83 for a one-week interval and the bi-factorial (visual and kinesthetic) structure of the questionnaire with the visual and kinesthetic subscales being separate, but related constructs (*r* = 0.58). Other studies support these psychometric properties of the MIQ (e.g., Atienza, Balaguer, & Garcia-Marita, 1994).

To create a simpler and shortened version, Hall and Martin (1997) modified the MIQ in order to reduce administration time, improve the efficiency of its administration, and eliminate tasks that were often omitted because of difficulty (i.e., front roll) and redundant movements. In addition, in Hall and Martin's (1997) revision of the MIQ (MIQ-R) the rating scale was reversed so that higher scores reflect better imagery ability and lower scores reflected poorer imagery ability, addressing noted counterintuitive weakness of the MIQ and the VMIQ-2. As a result, the MIQ-R assess the ability to mentally see and feel four movements (e.g., knee lift, jump, arm movement, and waist bend) that are individually summed to represent total visual (4-28) and total kinesthetic (4-28) movement imagery ability. Similar to the VMIQ-2, some studies used a composite MIQ-R score where at least a 16 on the visual and 16 on the kinesthetic subscales indicates adequate imagery ability (Callow et al., 2006); others have used a more stringent scoring criteria of at least 20 (Short & Short, 2005).

Psychometric properties of the MIQ and MIQ-R include significant correlations between the two questionnaires ($r = -0.77$, n = 50, $p < 0.01$, for each scale) (Hall & Martin, 1997), indicating that the MIQ-R is an acceptable revision of the original MIQ. Additional analyses showed consistent Cronbach alpha coefficients above 0.79 for both visual and kinesthetic scales (Abma, Fry, Li, & Relyea, 2002; Atienza et al., 1994; Hall et al., 1985; Vadocz, Hall, & Moritz, 1997), and test-retest reliability coefficients of 0.80 (VI) and 0.81 (KI) (Monsma, Short, Hall, Gregg, & Sullivan, 2009). Further, an MTMM approach to CFA was completed to examine if it provided a better model than a first-order CFA. Results illustrated that a CTCU model provided the best fit to the data, χ^2 (15) = 25.99, $p < 0.01$; RMSEA = 0.04, CFI = 0.99; SRMR = 0.03, with factor loadings ranging between 0.70 and 0.84 ($r = 0.23$) (Williams et al., 2012).

Despite good psychometric properties, the MIQ-R did not distinguish between imagery perspectives (Roberts et al., 2008), whether the image is seen from an IVI perspective or an EVI perspective. Using the VMIQ-2 as a model, this prompted Williams et al. (2012) to develop the MIQ-3, which includes three subscales assessing EVI ("when you watch yourself performing the movement from an outside point of view or third person perspective"), IVI ("when you watch yourself performing the movement from an inside point of view or first person perspective"), and KI ("the feelings and sensations experienced if you were actually producing the movement"). The four movements from the MIQ-R are imagined three times; one for each subscale, and the seven-point Likert scale was retained ranging from one ("very hard to see/feel") to seven ("very easy to see/feel"). The MIQ-3 consists of 12 items in order to provide an assessment of the inter- and intra-subject differences between the imagery conditions. Higher scores on a MIQ-3 scale represent a better ability to perform visual or kinesthetic imagery; scores ranging from 4-28 for each imagery condition.

Williams et al. (2012) illustrated that all three subscales of the MIQ-3 displayed adequate internal reliability ($\alpha > 0.69$). Further psychometric analysis of the MIQ-3 showed that a three factor CTCU model provided the best fit to the data, $\chi^2(39) = 75.12$,

$p < 0.001$; RMSEA = 0.05, CFI = 0.98; SRMR = 0.04, with standardized factor loadings ranging between 0.64 and 0.81, $p < 0.001$. The concurrent validity between the MIQ-3 and VMIQ-2 was also examined showing the covariances to be significantly correlated between all VMIQ-2 and MIQ-3 subscales: EVI, $r = 0.679$; IVI, $r = 0.328$; KI, $r = 0.706$ ($p < 0.001$), indicating that the subscales for each questionnaire are separate, but related constructs, providing a comprehensive assessment of MI ability. Moreover, support for the MIQ-3's concurrent validity was examined with the correlations between the VMIQ-2 and MIQ-3 subscales. Data revealed significantly higher correlations between respective subscales (EVI, $t = -2.40$, $p < 0.05$; IVI, $t = -5.92$, $p < 0.01$; and KI, $t = -4.06$, $p < 0.01$) compared to correlations with other types of imagery (Williams et al., 2012).

In general, both the MIQ-3 and VMIQ-2 measure the imagery ability of an individual, but they do so by using two different approaches to imagery ability. The MIQ-3 includes specific instructions asking participants to focus on the level of ease in generating the image. In addition, it takes the unique approach of having the participant physically perform each movement before subsequently imaging the movement in the specific modality. Two drawbacks of the VMIQ-2 are addressed by the MIQ-3. First, it eliminates any potential recency effects by having the participant practice the movement before engaging in imagery compared to the VMIQ-2 relying on recalling the movement from long term memory. Because previous literature has shown that how easily a movement is imagined may be affected by whether this movement was performed recently or frequently (Lequerica et al., 2002), the MIQ-3 instructions involve participants completing the movement physically before imaging the movement. The

MIQ-3 protocol also serves as a manipulation check of the participant's ability to do the movement, with scores more likely to be an accurate reflection of the participant's actual imagery ability rather than whether, or how recently the movement was physically performed. On the other hand, the VMIQ-2 instructions only present the imagery movement in a written form forcing participants to recall information about the task from long-term memory in order to generate the required image (Munzert & Zentgraf, 2009). This may produce varying images of the movement from person to person depending on personal experience and how they interpret the instructions or whether they are capable of doing the movements. Furthermore, by having participants perform the movement physically before engaging in imagery, the MIQ-3 provides the opportunity to visually confirm whether participants correctly understand the desired movement before it is imaged. Through this process, physically performing the movement will prime the brain regions that will later be utilized when the individual engages in imagery. In addition, the MIQ-3 instructs participants to mentally perform all of the movements from a starting position when physically performing the movements. This will likely increase the functional equivalence at the neural level between MI and ME and provide a more accurate assessment of a participant's imagery ability compared with a seated position for the VMIQ-2 protocol. Some researchers contend that measurement attributes of the MIQ-3 are likely to enhance the ease of imaging the movement perhaps inflating imagery ability scores (Williams et al., 2011).

Limitations. On their own, subjective questionnaires, especially those involving movement are limited in several ways. First, scores may not be distinguished between assessments of imagery ability or the ability to execute movements. Second, determining an individual's imagery ability on an ordinal rating scale involves inconsistencies between two given rating scores; a rating of a four may not be twice as easy as a rating of a two. Moreover, one individual's rating of a four may be quantifiably different in neuroactivity compared to another individual's same rating. Although there is an increased reliability with more scale points (Nunnally & Bernstein, 1994), the scales used for some of these questionnaires have inverse anchors (i.e., VMIQ-2: 1 = good and 5 = poor) which is contradictory to what most individuals understand as a higher number being better. Third, some self-report questionnaires lack a firm and objective frame of reference; consequently, their use is ambiguous and leaves room for subjective interpretations. Kaufmann (1981) argued that it can be difficult for individuals to rate their imagery experience on a Likert scale because similar mental experiences may be given highly varying values by different participants. Furthermore, memory decay involved in the retrospective recall of movement experiences can alter participant's response caused by how recent they completed this movement. While, the MIQ protocol reduces the time between ME and imagery of the movement, current neurological measures can improve this limitation because they enable the assessment of imagery concurrently with the reported experience.

Fourth, the use of self-report measures has been shown to cause participants to be subconsciously susceptible to response sets (Mischel, 1968). As with self-report questionnaires in psychology, a response set is the tendency of an individual to present a particular pattern of responses independent of what the question is asking (Peer &

Gamliel, 2011). Participants may provide response patterns that are in line with the study's goal, or as a way to make a good impression or to put oneself in a favorable light. For example, a response set might be to favor one of the numbers of the scale such as choice "3" or "somewhat hard to see" on the MIQ-3 because of the central tendency of participants to avoid the extreme ends of scales and choose the responses in the middle. Even if numbers are not present on a questionnaire, participants may continue to follow a response pattern, which introduces a difficult interpretation of the scores based on content (Cronbach, 1946). Therefore, any relationship between performance outcome and self-reported imagery ability may merely reflect the underlying response set that guides the score. To overcome this limitation, researchers can psychometrically evaluate the validity of questionnaire items used to measure the construct utilizing multiple factors to control method variance (i.e., MTMM model) (Campbell & Friske, 1959) or a CFA, as well as providing verbal labels for the mid-points of the scale instead of numerical values (Tourangeau, Rips, & Rasinski, 2000) and writing items that are clear and simple.

Lastly, self-report questionnaires are also criticized on the grounds of validity, reliability, and generalizability (Campos & Perez, 1990; Hall et al., 1985; Williams, Rippon, Stone, & Annett, 1995), often yielding discrepant results across samples and studies. Studies usually show adequate reliability as well as construct and concurrent validity but most often with other sources of subjective data. Specifically, an argument that continues to resonate was first proposed by Katz (1983) stating that questionnaires fail to meet the level of complexity found in the area of mental test construction.

Therefore, current researchers need to consider how a questionnaire was originally developed. More importantly, how individual items used to infer imagery were devised should be carefully considered in order to ensure the most appropriate distribution of item scores. Results need to be individually analyzed at the item level, especially according to each condition or scale. These previously mentioned limitations may influence the overall use of self-report questionnaires and explain why equivocal results are often found when studying individual differences (Kaufmann, 1981). Only when researchers can demonstrate the convergent validity of self-report imagery ability questionnaires with an objective measure (i.e., fMRI) will it be appropriate to draw suitable conclusions based on the evidence they generate.

Objective Measures

Several studies using objective measures have provided information about the nature of imagery. The measurement of psychophysiological responses in these measures can be regarded as a “window” into the brain during imagery (Hugdahl, 1995). Trying to understand the relationship between mental and physiological processes, researchers have developed various psychophysiological measures (i.e., peripheral: measures related to the peripheral nervous system; and central: measures related to CNS responses, including the brain) making research on aspects of MI easier to collect.

Imaging an action can have very similar physiological effects to those that occur during actual performance of that same action (Jeannerod, 1997), and can be recorded during MI. Common psychophysiological measures used in imagery research include transcranial magnetic stimulation (TMS), positron emission tomography (PET), functional magnetic resonance imaging (fMRI), electroencephalography (EEG), and magnetoencephalography (MEG). Although these measures produce converging evidence of the neural networks that mediate perception and the imagery experience (Kosslyn et al., 2001), they differ in their spatial and temporal resolutions, but still supplement our understanding of neural networks that mediate the MI experience (Guillot & Collet, 2010).

Transcranial magnetic stimulation is a noninvasive method that uses electromagnetic induction to induce weak currents in a rapidly changing magnetic field, and measures the consequences on inducing this electrical current in terms of motor excitability. Positron emission tomography is an invasive nuclear medical imaging technique that produces three-dimensional images of functional processes in the body and records positrons (atomic particles) emitted by radioactive isotopes injected into the blood. Functional MRI is a noninvasive functional neuroimaging procedure that maps the structures of the brain by detecting associated changes in blood flow following the excitation of atoms through radio waves. It is capable of detecting hemodynamic changes throughout the brain through the BOLD effect. Both fMRI and PET have good spatial resolution, but poor temporal resolution. In contrast, EEG is the recording of electrical activity of the brain using electrodes placed on the scalp and MEG is a neuroimaging technique that records magnetic fields produced by electrical currents that are naturally occurring in the brain. Although both of these techniques have good temporal resolution, they have less spatial resolution so they will not be included in this review.

Brain imaging techniques have been most significant in advancing our understanding about the gross structures of the brain and how living systems function (Tancredi & Brodie, 2007). Given its complex nature, imagery depends on various mechanisms located in different regions of the brain rather than single “brain centers” (Erlichman & Barrett, 1983; Farah, 1984; Kosslyn, 1994, 1987). Built around a cognitive and affective neuroscience perspective, studies using brain mapping techniques have allowed researchers to begin to understand the neurobiology underlying higher order mental processes such as mental imagery. More importantly, these techniques can also begin to provide evidence that can validate imagery questionnaires at the item level. Therefore, the following sections will review the most relevant methodologies in the neuroscience research as it applies to imagery, particularly fMRI.

Several functional neuroimaging studies have demonstrated that MI is associated with the specific activation of the neural circuits involved in the early stages of motor control (i.e., motor programming and movement preparation). Recent studies utilizing fMRI have indicated that executed and imagined movements produce similar brain activity (Jeannerod, 2001; Gerardin et al., 2000; Guillot et al., 2008; Higuchi, Imamizu, & Kawato, 2007; Imazu, Sugui, Tanaka, & Inui, 2007; Lacourse, Orr, Cramer, & Cohen, 2005; Lotze et al., 1999; Nair et al., 2003; Szameitat, Shen, Conforta, & Sterr, 2012). The neural circuits involved include the SMA, M1, PMC, inferior parietal cortex, basal ganglia, and cerebellum (Decety et al., 1994; Roth et al., 1996). Although some studies have used self-report imagery ability questionnaires as a screening tool to separate participants into good and poor imagery groups based on ability level (Amedi et al., 2005; Belardinelli et al., 2009; Cui et al., 2007; Guillot et al., 2008; Lacourse et al., 2005), it is still unclear whether these measures can differentiate between good and poor imagers and truly tap the construct of movement imagery ability. The following sections provide a summary of the extant literature examining the association of similar brain activity produced by physically executing and imaging movements using functional neuroimaging techniques, and will be organized according to movement type (i.e., non-functional and functional), providing a general introduction followed by associated research as well as its advantages and limitations.

Transcranial magnetic stimulation. Transcranial magnetic stimulation is performed by using electromagnetic induction to stimulate weak electrical currents into the brain in order to cause the depolarization or hyperpolarization in the neurons of the brain. Motor evoked potentials (MEPs) are recorded in response to the excitability of corticospinal neurons; the higher the excitability, the larger the MEP amplitude.

Using TMS, it has been shown that the MEP amplitude of the flexor carpi radialis muscle increased during imagery of wrist flexion demonstrating that MI can raise the corticospinal excitability above the resting excitability level (Kasai, Kawai, Kawanishi, & Yahagi, 1997). Subsequent studies confirmed this phenomenon (Fadiga et al., 1999; Fadiga et al., 1995; Hashimoto & Rothwell, 1999; Li, Latash, & Zatsiorsky, 2004). For example, Fadiga et al. (1995) examined MEPs of 12 participants (gender not provided) by stimulating the left motor cortex during four experimental conditions: (1) grasping observation, (2) object observation, (3) arm movement observation, and (4) dimming detection. The results showed that the motor system increased in excitation when a participant observes another individual performing the action (both grasping and arm movement tasks). Moreover, the pattern of muscle contraction during observation was found to be similar to the pattern of muscle contraction present during ME of the same action. Using a similar TMS protocol, Fadiga et al. (1999) investigated whether corticospinal activity is specifically affected by MI by recording MEPs from six right-handed participants (two males and four females) during MI of flexion/extension movements of the right hand and wrist muscles. Increased corticospinal excitability of the left primary motor cortex during imagined ipsilateral and contralateral hand movements was found, as well as a facilitatory effect induced by imagery of contralateral hand movements of the right primary motor cortex. These results confirm that the mental simulation of movements involve the same neural substrates that are addressed during ME, and that MI manifests itself in the activation of the same cortical circuits that are normally involved in actual movement. Similar to the MIQ protocol, movement observation prior to imagery in this study also served as a manipulation check to control for temporal movement experience variability, helping standardize participant’s experience.

In two more recent studies, Mizuguchi et al. (2009, 2012) investigated the influence of external sensory input (i.e., engaging in ball squeezing) on corticospinal excitability in conjunction with MI. Their initial study (2009) analyzed the corticospinal excitability of participants imaging the squeezing of a ball both with and without holding the ball in two experiments: TMS (16 males) and somatosensory evoked potentials (SEPs) (10 males). The TMS experiment included four conditions: (1) control condition,

(2) holding condition, (3) MI condition, and (4) MI and holding condition, while the SEP experiment included five conditions: (1) control condition, (2) holding condition, (3) MI condition, (4) MI and holding condition, and (5) execution condition. Overall, the TMS experiment indicated that during imaging the ball squeezing MEP amplitude increased compared to when the ball was passively held. However, the SEP experiment did not show a difference in amplitude when imaging the action or holding the ball. It was concluded that corticospinal excitability can be enhanced when holding an object, but not by changing stimuli along the afferent pathway to the primary sensorimotor cortex.

Their follow-up study (Mizuguchi et al., 2012) investigated whether corticospinal excitability when imaging squeezing a ball is affected differently by holding a ball on the ipsilateral versus contralateral side to the imagined action. This study consisted of two experiments with 10 right-handed individuals (no gender provided) participating in each. In the first experiment, participants imagined squeezing a ball with the right hand using three conditions: (1) null condition, (2) right condition, and (3) left condition. In the second experiment, the participants imagined squeezing the ball with the left hand while completing the same conditions as experiment one. While completing each condition, TMS was delivered, as well as simultaneous EMG from four hand and forearm muscles on both sides. Both experiments confirmed the previous finding that MEP amplitude during imagery tasks was increased by passively holding a ball in the same hand that one was imaging, and no significant effect occurred when holding a ball with the opposite hand of imagery. Therefore, these studies suggest that only somatosensory signals from the ipsilateral hand that is being imagined is integrated in the process of MI.

External sensory input, especially its maintenance during imagery and imaging movement in the dominant side without varying the side are important design features gleaned from these studies. The major advantage of TMS is its ability to stimulate the brain and deep peripheral nerves without causing harm and discomfort to the participant. It is particularly useful in studying the precision of timing of effect of cortical function. However, the precision of defining the site of mental stimulation effects is currently inferior to that achieved with other techniques such as PET and fMRI.

Positron emission tomography. Positron emission tomography is a functional imaging technique performed by introducing a radioactive material (i.e., tracer) into the body in order to show the size, shape, and position of organs and tissues as well as how they are functioning. Pairs of gamma rays emitted indirectly by the tracer are detected to produce three-dimensional images of tracer concentration within the body constructed by computer analysis.

Previous research (Yue & Cole, 1992) using PET suggests that MI is functionally close to the preparatory and executive processes of ME. Initial studies (e.g., Ingvar & Philipson, 1977) found that similar areas of the brain were activated when participants completed a physical task or when they imaged the same task, showing similar increases in the premotor and frontal regions of the brain. Additional research was completed to map motor representations regarding hand movement tasks (Decety et al., 1994). Using PET, cerebral brain activity was mapped in six right-handed male participants that completed two activation conditions (movement observation and MI) and one control condition (visual inspection) while changes in rCBF were measured. The results of this study provided additional insight into the mechanisms operating during the representation of motor activations. Particularly, it was found that consciously representing an action involves a pattern of cortical and subcortical activation that is similar to that of an executed action in the cognitive stages of motor control.

Subsequent research established that individuals can experience vivid MI primarily involving a kinesthetic representation of actions (Lotze et al., 1999) leading to the proposal that MI may contain kinesthetic sensations as well. In order to test this hypothesis, Naito et al. (2002) evaluated the effect of MI during palmar flexion of the right wrist. Ten healthy, right-handed males were selected and trained for approximately two weeks to imagine slow wrist movements of alternating palmar flexion and dorsiflexion, after which rCBF of each participant was measured when completing the above tasks. Areas in the left cingulate motor area, SMA, dorsal PMC, and the right cerebellum were activated during MI. These results support the claim that imagery reflects the predicted sensory effects of one’s actions on sensory processing areas without the actual sensory input. In other words, internally simulated movement sensations are activated during MI through the recruitment of multiple motor areas and the cerebellum, without the maintenance of external stimulation as in Mizuguchi et al. (2009, 2012).

Unlike other neuroimaging techniques, PET can measure metabolic changes that occur at the cellular level in an organ or tissue indicating blood flow as well as oxygen and glucose metabolism in working brain tissues. Although small movements that occur during the scanning process do not result in artifacts, the image produced by PET is not as clear as other techniques (i.e., fMRI). Furthermore, because PET introduces a short-lived and rapidly decaying radionuclide into the body, it is limited in that it only allows for the examination of brain activity resulting from brief tasks. The generalizability of tasks longer duration such as gross motor movements common in MIQ-3 and VMIQ-2 are thus limited.

Functional magnetic resonance imaging. The evolution of brain mapping techniques in cognitive psychology and related disciplines has begun to rely on fMRI as a powerful method to measure brain responses to cognitive tasks, providing greater detail and resolution than other methods (i.e., PET and EEG). Functional MRI is a tool that allows for the integration of anatomical, neural, and molecular information in a single session (Amaro & Barker, 2006; Porro et al., 1996; Tancredi & Brodie, 2007; Vaghela, Kesvadas, & Thomas, 2010). These benefits allow fMRI researchers to evaluate the activation and effective connectivity of the neural networks involved during different tasks in relation to MI and ME. Merging imagery with neuroimaging measurement paradigms, especially fMRI, has the potential to provide further neural network activity support for the simulation theory (Jeannerod, 2001) specifically when validated against the real-time imagery simulation states that are part of the MIQ-3. The practical essence of measuring “real-time” imagery with fMRI technology is also important to support the continued use of questionnaire-based imagery assessments frequently used in the field.

Understanding the neural correlates that pertain to physically performing upper and lower extremity movement tasks and how they relate to imaging these same tasks can be beneficial in the development of research designs and provide insight regarding the mechanisms that facilitate imagery ability. However, this is difficult because of the distributed nature of the neural networks used in brain processing, in which multiple regions are involved for a single task. As previously described, the brain is functionally organized in which specific regions are responsible for movement planning/preparation (i.e., SMA, parietal cortex, insular cortex, cingular gyrus, superior frontal gyrus, and PMC) and ME (i.e., precentral gyrus, superior parietal lobule, SMA, cingular gyrus, inferior parietal lobule, and M1). Many studies utilizing fMRI that report activation of motor regions have been limited to using movements which are non-functional or require minimal effort, including sequential finger movement tasks (Mayka, Corcos, Leurgans, & Vaillancourt, 2006). Such tasks do not represent functional or skilled movements (e.g., reaching and grasping, tool-use, and gait) as would be used in activities of daily living. Therefore, the neural correlates shared between ME and MI will be illustrated according to non-functional and functional movement tasks.

Non-functional movement tasks. Early neuroimaging research typically relied on non-functional movement task paradigms (i.e., finger-tapping and sequential finger tasks) to study the human motor system. Non-functional movement tasks usually require participants to perform movements using fingers two through five on a four-key response device or using one finger to tap a specific sequence. In order to associate MI and ME these tasks are assessed on the accuracy and movement time of the performed task. Specifically, Roa et al. (1996) indicated that a positive linear relationship exists between movement rate and fMRI signal change, as well as a similar number of voxels significantly increasing demonstrating functional equivalence during tasks. These tasks have the advantage of being simple to use with both normal participants and patients with neurological disorders that affect the motor system, being flexible to accommodate various modifications (i.e., pacing and complexity), and the ability to complete these tasks inside and outside of the scanner. However, results can be divergent because of variations in the experimental paradigms used making them difficult to interpret and generalize across studies (Witt, Laird, & Meyerand, 2008).

Studying the overall activated brain areas using non-functional movement tasks, Porro et al. (1996) completed a study examining the primary motor and sensory cortex during motor performance and MI. Fourteen right-handed participants (four males and 10 females) completed a self-paced finger-to-thumb opposition movement task of the dominant hand in order to investigate the activated foci during MI and ME in the postcentral gyrus as well as the anterior and posterior portions of the precentral gyrus. Results indicated an increase in the overlapping neural networks in the primary motor and sensory cortex areas (i.e., precentral and postcentral gyri) during both motor performance (mean percentage increase, 1.7%) and MI (0.6%), although the intensity of activation is lower than during actual ME. Although results suggest that the primary motor cortex is involved during MI, this may have been observed because gradient-echo fMRI sequences are sensitive to inflow and large vessel effects causing the effective spatial resolving power to be hampered producing unrelated brain activity. In addition, since fMRI has poor temporal resolution, fast hemodynamic changes could not be detected because of the quick rate of the movement task.

This work was followed by Lotze et al. (1999) investigating the activation in the primary and secondary motor areas during ME and imagery of the dominant and non-dominant hand of 10 right-handed participants (five males and five females). During high spatial fMRI, participants were instructed to make a fist and then imagine making a fist at a specific rate, first with the right-hand and then with the left-hand. Prior to image acquisition, participants were trained with low EMG activity of the flexor digitorum superficialis muscle and high vividness of the imagined movement. A region of interest analysis of activated voxels above a t-value of 2.45 ($p < 0.01$) showed that the same cortical regions were active during ME and MI (i.e., SMA, PMC, and M1) as well as the cerebellum, but to a lesser degree. In addition, the somatosensory cortex was significantly activated but only during ME. The cortical activity recorded in this study demonstrates support for the hypothesis that MI and ME share similar neural substrates (Jeannerod, 1994).

This prompted Gerardin et al. (2000) to compare MI and ME of simple (simultaneous flexion/extension of the fingers) and complex (selective flexion/extension of the index and little finger) finger movements. Prior to imaging or executing auditory-cued finger movements, participants (right-handed, five males and three females, Mean age = 26.6 years, Range = 21-35 years) completed the MIQ-3 to determine if they were good (Score Range = 8-32) or poor (Score Range = 33-56) imagers. Analysis of the MIQ-R showed that participants had a mean visual vividness score of 16 ± 5.4 (Range = 10-22) and a mean kinesthetic vividness score of 17.9 ± 7.2 (Range = 9-26). Group analysis for the direct comparison between executed and imagined movement showed a significant activated network centered on the central sulcus (i.e., bilateral sensorimotor cortex, lateral PMC, post-SMA, anterior cingulate cortex, and ventral inferior parietal areas), as well as subcortically in the anterior right putamen, posterior left putamen, thalamus, and cerebellum. On the other hand, MI compared to ME indicated increased activation more rostral in the frontal lobes and more superior and caudal in the parietal cortex (i.e., superior and inferior parietal cortex, prefrontal cortex, pre-SMA, lateral PMC, right anterior cingulate cortex, left parietal lobes, basal ganglia, putamen, and caudate nucleus) ($p = 0.01$, non-corrected). More importantly, comparing complex and simple movements showed no significant activation differences. These results partially confirm that imagery of a motor act and its actual execution involve similar brain area activation (Decety et al., 1994; Grafton et al., 1996; Jeannerod, 1994; Rao et al., 1993; Stephan et al., 1995), with MI partially overlapping the same brain areas as ME but still having its own specific neural network.

Similar results were found using fMRI to compare the functional anatomy of ME and MI of 10 right-handed participants (seven males and three females, Mean age = 32 years, SD = 11 years) using a number-guided segmented sequential finger tapping task (Hanakawa et al., 2003). Overall, results indicated that ME activated the primary sensory and motor areas, parietal operculum, and anterior cerebellum which had little activity during MI (-0.1 – 0.1%) as well as the PMC and visual cortex which had mild activity during MI (0.2 – 0.7%), while areas predominantly activated during MI included the precentral sulcus and the posterior superior parietal cortex/precuneus. In addition, many of the frontoparietal areas and posterior cerebellum were activated in both ME and MI conditions. These results provided additional support for a functional shift from more imaginative properties to more motor executive properties in many cortical and subcortical areas (Gerardin et al., 2000; Stephan et al., 1995). However, false activation may have occurred because of the subtraction method used to analyze the data reflecting a difference between complicated responses and simple movement tasks. In addition, artifacts caused by mild muscle contractions and eye movements as well as the use of different imagery modes may have altered the results.

Unlike most fMRI studies using non-functional movements, Ehrrson, Geyer, and Naito (2003) expanded this area by investigating whether imagery of voluntary movements of different body parts correspond to body-part-specific motor representations. Seven right-handed (six males and one female, Mean age = 25) completed a training session of three ME conditions (flexion/extension movements of the fingers, flexion/extension movements of the toes, and horizontal tongue movements), three MI conditions (imaging the ME movements), six rest conditions serving as an independent baseline for each movement/imagery condition, and subsequently completed these same task conditions inside the scanner. Findings indicated that motor imagery engages somatotopically organized sections of the M1 in which each body part (i.e., hand, foot, and tongue) activated body-part-specific representations in primary and non-primary motor areas.

In order to further explore and expand the literature on the fine modulation in network activation during ME and MI, Solodkin et al. (2004) explored the inter-relationships among the relevant brain areas for VI, KI, and ME. After measuring EMG activity during execution of an unpaced thumb opposition movement as well as KI and VI of the movement, eighteen right-handed participants (nine males and nine females) were divided into two groups (KI and ME; VI and ME) and completed the same task inside the scanner. Intra-subject and inter-subject analyses were performed using a region of interest approach largely confirmed the functional anatomy of MI of previous studies (Fadiga et al., 1999; Jeannerod, 1995). In addition, the networks for ME, KI, and VI were statistically different, with the most notable difference between KI and ME in M1 suggesting that a physiological mechanism exists that prevents overt movements during imagery conditions.

Functional MRI was also utilized by Lacourse et al. (2005) to compare the functional neuroanatomy associated with executed and imagined finger movements according to novel and skilled learning phases. Using their right hand, 54 participants (19 males and 35 females) completed the MIQ (mean score = 22.6 ± 4.9), VMIQ (mean score = 94.3 ± 24.2), and a subsequent sequential button press task inside a scanner before (novel) and after (skilled) a week of intensive physical practice. Results indicated that skilled participants were significantly faster at executing the task compared to the novel participants ($p < 0.001$), but there was no difference in the amount of execution errors. Based on a voxel of interest analysis, it was found that congruent brain activations are associated with ME and motor imagery in both phases with clusters of activation in the M1, ventral PMC, primary somatosensory cortex, and SMA. Further analysis indicated that voxels of interest were more similar to ME in the skilled rather than the novel phase of learning. Congruent cortical and subcortical motor areas associated during both novel and skilled phases support the effectiveness of a MI based training program to acquire and rehearse skilled movements. However, there were two methodological flaws: (1) the use of a blocked design was not able to differentiate motor planning from ME, making it unclear as to whether the activation reflects differences in planning or execution or both, and (2) the use of multi-session learning may have caused the reproducibility of the BOLD signal such that non-specific within-session effects my confound the effects of learning.

More recently, Szameitat, Shen, Conforto, and Sterr (2012) investigated the activation of the sensorimotor system without overt movement during three covert movement modes (MI, passive movement, and movement observation). For this, 21 healthy, right-handed participants (11 males and 10 females) and five stroke patients were separated into one of the four movement conditions (i.e., execution, MI, movement observation, and passive movement) and underwent fMRI scanning. Results in healthy participants demonstrated that overt movements of the wrist activated a network of areas in the lateral sensorimotor cortices, medial motor cortices, and parietal areas. Like execution, imagery activated the SMA. However, unlike execution activating more primary motor cortices, imagery predominantly activated premotor and prefrontal areas which are associated with motor planning. In patients, the attempt to execute wrist movements extensively activated the sensorimotor network (primary motor and sensory areas) which was most like MI suggesting that imagery may be the best approach to activate the motor system in stroke patients. However, matched controls were not used in this study so caution should be taken when transferring results between patient samples and healthy participants.

Functional movement tasks. Recent neuroimaging research has moved toward using functional movement task paradigms (e.g., gait and tool use) to study how the brain functions during activities of daily living. Functional movements, as referred to in the following research, are those involved with larger, more complex gross motor movements that often have a specific purpose. Like non-functional movement tasks, functional movement tasks are also assessed on the accuracy as well as the imagery movement time of the task compared to its physical execution. However, because larger movements are involved they cannot be performed inside a scanner without producing artifacts in the data. Although direct comparisons cannot be made inside the scanner, using functional movements are the most important outcomes to pursue and measure (Uswatte et al., 2000) in rehabilitation and sport settings.

Within the fMRI research, a commonly used functional movement task paradigm is the ability to use a tool in order to detect apraxia. One of the most reliable predictors of actual tool use is the ability of an individual to pantomime the use of the same tool allowing for the collection of data regarding human hemispheric specialization for tool use. However, since the specific anatomic substrates of these tool use applications is still poorly defined Moll et al. (2000) conducted a study to identify the brain areas activated when one pantomimes the use of tools. While in an fMRI scanner, 16 (11 males and five females) right-handed individuals completed a tool use and shame (control) praxis in which each participant was asked to gesture the use of 24 common tools with a control task between each task, with eight of these participants being asked to imagine the execution of the task. A subtraction analysis was used to analyze five regions of interest of the cerebral hemisphere showing that the imagined performance of the same actions did not essentially change the cortical activations compared to the physical execution condition (i.e., parietal lobe, caudal dorsolateral frontal cortex of the left cerebral hemisphere, and inferior parietal lobule). Even though these results add to the notion that imagined and executed actions enlist the same brain regions, this study only used a small mixed-gender sample of participants to examine the activated areas in a superficial manner.

More recent studies using fMRI to focus on image vividness as a key to imagery ability have been completed by Higuchi et al. (2007) and Imazu et al. (2007) finding inconsistent results. They investigated brain activity in order to understand the difference in activity related to actual tool use compared to MI of tool use and infer the underlying neuronal mechanism(s) of these tasks. Blood oxygenation level-dependent contrast images of eight participants (five males and three females, 23-39 years old) were collected as each participant completed 16 tool grasping/tool use tasks in three conditions (imagery, execution, and control). A fixed effect analysis indicated that both imagery and execution tasks activated brain areas that were spatially close to each other (i.e., left M1, SMA, posterior parietal cortex, posterior inferior parietal sulcus, and right cerebellum). Although these results support previous findings suggesting that neural mechanisms contribute to skillful tool use, because muscle activation and sensory movement was not considered, brain regions may have been implicitly activated altering the true relationship between ME and MI tasks.

Contradicting results were found in a tool use study examining the differences between actual and imagined usage of chopsticks (Imazu et al., 2007). Twelve right-handed participants (six males and six females, Mean age = 26.1 years) performed the task of picking up and putting down pieces of plastic using chopsticks in their right hand across four conditions (tool use, tool mime, tool imagery, and hand imagery) while being scanned. Blood oxygenation level-dependent contrast images were obtained to indicate clusters of greater than five voxels that were activated during each condition. Unlike Higuchi et al. (2007), similar brain activation between execution and imagery was not directly found. Rather, evidence revealed that activation in the right lateral cerebellum and precentral gyrus increased during execution of tool use compared to the imagery condition (i.e., cerebellum, parahippocampal gyrus, corpus callosum, and inferior parietal lobule). Attaining such results may have been a result of using a well-learned and familiar tool use task that participants had already acquired the internal mode for and were not required to learn how to use this tool.

Functional MRI has also been used as a measurement technique to examine the functional neuroanatomical correlates of MI during more complex and larger everyday movements. Using more gross body movement tasks (i.e., tie shoelaces, swim, run, dance) Szameitat, Shen, and Sterr (2007) sought to determine which neural mechanism(s) are used during MI. Seventeen right-handed participants (six males and

11 females) imagined movements of their upper extremities (i.e., eat a meal with knife and fork, cut your fingernails with scissors, write on a piece of paper using a pen, shuffle and deal playing cares, tie shoelaces, brush/comb your hair, and button a shirt/blouse) and movements involving the whole body (i.e., swim, lift heavy boxes from floor to table, run, dance, throw and kick balls, dig a hole using a spade, and use a vacuum cleaner) during fMRI scanning. In addition, participants completed a post-scan questionnaire to ensure the vividness of the image was comparable between upper extremity and whole body movements. Vividness ratings were almost identical (Median upper extremity score = 6, Median whole body score = 6, Wilcoxon Signed Ranks Test z = -0.577, p = 0.564) in which all participants indicated good imagery quality (values ranged between four and seven for both movement types). Comparison tests indicated that MI of everyday movements activated the lateral and medial premotor and parietal cortices. The different movement types also showed a homuncular organization in sensorimotor cortices while resulting in the same activation in cortical areas. It is likely that the use of a wide variety of difficult movements led to spatially more extended cortical activations and smaller individual variability compared to using a simple functional movement task to indicate more localized and greater individual variability. However, from a methodological standpoint, physical constraints may make it unlikely to show tendencies to execute the movement (e.g., running while lying supine in the scanner), using highly familiar everyday movements preventing the control of familiarity, and not controlling for variables such as intensity and frequency of imagery.

Concurrent fMRI research developed a new experimental protocol to quantify the imagery of gait (Bakker, de Lange, Stevens, Toni, & Bloem, 2007) showing that movement time increased with increasing path length and decreasing path width in three conditions (actual walking, MI, and VI). In addition, the effect of the path width on movement times was significantly stronger during MI and actual walking compared to the VI condition. In their follow up study, they used the previously validated MI protocol (Bakker et al., 2007; Stevens, 2005) to examine the cerebral correlates of MI during normal and precision gait (Bakker, de Lange, Helmich, Scheeringa, Bloem, and Toni, 2008) as well as the motoric specificity of the effects and the effector specificity of MI of gait. Results of 16 right-handed males (Mean age = 22 years, SD = 2) completing two tasks, MI and VI of gait, indicated that imagery movement times were longer for the narrow path during MI, compared to VI, suggesting that MI is sensitive to the environmental constraints of a narrower path. In addition, cerebral activity (i.e., superior parietal lobule, frontal cortex, right cingulate gyrus, and left putamen) was increased during this task emphasizing the role of cortical structures outside the primary motor regions in imaging locomotion movements when precision is required. Although, imagery-related effects were distinguished which were influenced by environmental constraints and controlled for changes in muscle activity, certain methodological flaws should be addressed so as to not influence the evidence obtained relating to the MI experience: (1) task settings, including the participant’s posture and the imagined gait being performed while sitting in a chair and not in a gait initiation position; (2)

researchers providing each participant with different instructions; and (3) using tacit knowledge to estimate the time to actually execute the movement.

Improving upon these limitations, Iseki, Hanakawa, Shinozaki, Nankaku, and Fukuyama (2008) examined the brain activity during observation and imagery of gait to test the hypothesis that visual stimuli would assist in invoking motor planning programs and produce active mental rehearsal of motor acts. Unlike previous studies, fMRI was used in a virtual reality environment that supplied realistic visual feedback to the participant which mimics real walking to assess activation of the motor network during imaginary gait. Using this paradigm, 16 right-handed participants (13 males and three females) completed six behavioral conditions in which different types of video clips were shown: (1) gait observation, (2) stepping observation, (3) standing observation, (4) scramble gait observation, (5) virtual walking, and (6) scrambled virtual walking. Participants subsequently evaluated the vividness of the mental image of their virtual walking experience on a five-point scale (1 = image as vivid as normal vision and 5 = no image at all). It was found that participant's mean vividness rating of the mental image was three (SD = 0.8), and that there was a significant correlation between virtual and actual walking for each individual level ($r = 0.67=0.95$, $p < 0.05$ for each subject) as well as in the pooled data for all subjects ($r = 0.78$, $p < 0.01$) indicating that gait imagery within the virtual walking stimuli paradigm had a motor/kinesthetic aspect. In addition, common activity between observation and imagery was found in the SMA and M1 suggesting that motor planning centers of gait are activated during both imagery (first-person perspective) and observation (third-person perspective) of gait behaviors.

Similarly, cortical control of gait-related imagery of 21 right-handed gender-balanced participants (Mean age = 21.5 years, SD = 1.2) was examined during imagery of the initiation of gait, stepping over an obstacle, and the termination of gait from a first-person perspective (Wang et al., 2009). Prior to being scanned, the paradigm was presented to the participants outside of the scanner. For each experimental condition, participants watched a video clip of the task and then were instructed to mentally imitate the movements viewed in the clips. Cortical activation recorded by fMRI indicated the following results for each gait task: gait initiation – primarily activated the SMA to control movement preparation and ME (Cunnington, Windischberger, Deecke, & Moser. 2003; Picard & Strick, 2001); stepping over an obstacle – primarily activated the SMA, posterior/superior parietal cortex, MT/V5, and PMC providing dynamic balance and controlling foot trajectory over obstacles (Reynolds & Day, 2005); and gait termination – primarily activated the prefrontal area (i.e., inferior frontal gyrus and the pre-SMA) and the superior temporal gyrus contributing to the response inhibition process (Coxon, Stinear, & Byblow, 2009; Leung & Cai, 2007; Xue, Aron, & Poldrack, 2008). Although this study did not directly monitor imagery performance and analyze each imagery mode separately, it demonstrated that cortical control is important during functional movements, especially the different phases of gait.

Despite existing studies on locomotion, the brain network(s) used during real locomotion has yet to be examined. Therefore, la Fougere et al. (2010) proposed a new method to investigate brain activation during real steady-state locomotion using [18F]-FDG PET and BOLD response in fMRI. Sixteen right handed participants (nine males and seven females, Mean age = 61.3 years, SD = 7.8) without gait disorders completed a locomotion paradigm in which they walked for 10 minutes at a comfortable speed prior to and after a [18F]FDG after which image acquisition was obtained by PET. The fMRI portion of the study instructed participants to imagine themselves in the lying (rest condition), standing, walking, and running conditions, as they had practiced in an earlier training session. The direct comparison of real and imagined locomotion showed a brain network consisting of activation of the midline cerebellar areas (vermis, paravermis, and cerebellar locomotion regions), occipital visual cortices (cuneus and precuneus), parahippocampal gyrus, and fusiform gyrus. A major difference found was that M1 was activated during real locomotion, while the SMAs (superior/medial frontal cortex and dorsolateral prefrontal cortex) and basal ganglia (caudate nucleus and putamen) were activated during motor imagery. This may occur because imagery may only activate a premotor planning mode of locomotion, whereas the mode of real locomotion travels directly from the primary motor areas (Hanakawa et al., 2008). Therefore, real steady-state locomotion represents a direct pathway as measured through PET, while imagined locomotion encompasses an indirect pathway measured by BOLD fMRI which supports claims found by Wang et al. (2009).

Subsequent to their aforementioned study, Szameitat, McNamara, Shen, and Sterr (2012) used fMRI to investigate the functional neuroanatomical correlates of bimanual coordination demands in MI of everyday actions compared to unimanual movements. The imagery of unimanual actions as well as bimanual actions of 17 participants (six males and 11 females, Age = 19-31 years) were completed in five conditions (bimanual, simple-left, simple-right, complex-left, complex-right, and baseline) while being scanned. A significant increase was not found in overall neural activation during MI of bimanual actions compared to MI of unimanual actions, but the data confirmed that by increasing the complexity of the action increases the connectivity between brain areas. In addition, data from these participants supported previous studies (Bakker et al., 2008; Hanakawa et al., 2003; Porro et al., 1996) showing increases in connectivity between parietal and premotor areas within and between the left and right hemispheres. These findings provide additional support for the assumed equivalence of overt and imagined (covert) actions of bimanual and unimanual activities of daily living.

Lastly, recent investigations have used fMRI to examine the neuronal involvement activated during MI of an action with an object both with and without passively holding the object (Mizuguchi et al., 2013). Prior to the experiment, (17 males and two females, Mean age = 25 years, SD = 2) MI vividness was assessed on a seven-point Likert scale (7 = vivid imagery and 1 = not vivid imagery) according to three tasks: (1) imaging squeezing a foam ball with the right hand while holding the ball with the right hand, (2) imaging squeezing the ball with the right hand while holding nothing, and (3) passively holding the ball with the right hand without MI, and then completed these tasks in the scanner. Imagery vividness scores were significantly better in the imagery with ball condition (6.5 ± 0.2) compared to the imagery condition without a ball (5.1 ± 0.3) ($p < 0.01$). First-level and second-level data analyses revealed activation in the SMA, dorsolateral prefrontal cortex, parietal cortex, cerebellum, and basal ganglia during MI suggesting that the frontoparietal networks are mainly involved in the MI of an action while holding an object.

The generalizability of the aforementioned results obtained by fMRI should be carefully considered because of the various procedures used to complete each experiment as well as the various data analysis techniques. Nevertheless, research utilizing fMRI has generally shown that MI and ME continually produce similar brain activity suggesting that neural substrates are equivalent (e.g., Imazu et al., 2007; Roa et al., 1993).

Limitations. Although fMRI is considered a sensitive method to objectively measure functional brain activity, several restrictions limit the generalizability of the data because of the various protocols and data analysis strategies that can be used. With this in mind, it is important to recognize that the BOLD response is an indirect measure of neural activity and that results obtained from each experiment can significantly be altered through confounding factors (i.e., noise, head movement, instructions, muscle activity, and changes in brain state environment) (Vaghela et al., 2010). In addition, although images can be collected quickly, which should allow for good temporal resolution, the temporal resolution is limited by the hemodynamic response which delays the fMRI signal and a finite signal-to-noise ratio. For example, if a temporal difference is observed in two distinct brain regions, it may represent a temporal difference or a difference in the hemodynamic response characteristics of the two regions. Unless deconvolution methods are applied or the regions of interest are spatially distinct, the temporal difference should be carefully evaluated when using MC paradigms in fMRI research. Moreover, current fMRI research typically does not include EMG to regress out muscle activation artifacts which may alter the brain activation pattern during MI since it has yet to be determined if this activity is localized to the specific muscle(s) involved in the movement being imagined or if they are a by-product of central changes in the CNS. Overall, neuroscience measurement paradigms have indicated the usefulness of neuroimaging techniques to better understand the relationship between MI and functional brain processes at a higher level than self-report measures (Guillot & Collet, 2010).

Recent literature continues to show little evidence of a link between self-report questionnaires and relevant observable events, leaving the question open whether these measures truly tap the construct of imagery ability (Lequerica et al., 2002). As suggested by previous literature (Collet et al., 2011; Guillot & Collet, 2005; Roure et al, 1999), subjective measures should ideally be combined with more objective measures (i.e., chronometric measures, psychophysiological measures, and neurophysiological measures) that complement the information garnered from these measures. More importantly, the convergent validity of self-report measures should be examined according to objective physiological measures that record activated neural substrates during MI specifically at the item level and ideally at the same time participants are engaging in specific types of imagery.

Combining Subjective and Objective Measures

It is not unusual to use multiple measures across subjective and objective paradigms to examine a dependent variable; in this case, MI. However, when both are used it becomes questionable as to whether they are measuring the same underlying construct. Previous imagery research suggests that there is not a consistent relationship between self-report questionnaires and objective measures (Ernest, 1977; Danaher & Thoresen, 1972; Marks, 1972; Rehm, 1973; Richardson, 1977; Rimm & Bottrell, 1969) because of the inadequate measurement of individual differences within each measure (Hall et al., 1985). This was initially discussed by Richardson (1977) and Di Vesta et al. (1971) finding that these two types of tests should load on factors that are orthogonal to one another, while other correlational and factor analytic studies have repeatedly shown that self-report and objective measures are largely unrelated (Burton & Fogarty, 2003; Lequerica et al., 2002; McLemore, 1976; Moreau, Clerc, Mansy-Dannay, & Guerrien, 2010; Poltrock & Brown, 1984).

The argument that the subjective experience of imagery may not actually indicate a strong relationship to any measurable capacity (Neiser, 1970), and that reliable physiological correlates of subjective imagery reports are elusive (Campos & Perez, 1990; Paivio, 1973, 1971; Richardson, 1969; Williams et al., 1995) still remains today. Because recent literature continues to show little evidence supporting a link between self-report questionnaires and relevant observable events it is unknown whether these measures truly tap the construct of imagery ability. Measurement protocols such as mental rotation tasks, including the paper folding test, cube-cutting task (i.e., Necker Cube), Gordon Test of Visual Imagery Control, VMIQ, and MIQ have been used to assess imagery ability, and have been found to have good psychometric properties. Lequerica et al. (2002) used these measurements to test the hypothesis that imagery control is best assessed by measures that tap vividness of static images. Descriptive correlations of 80 participants (39 males and 41 females, Mean age = 22.1 years, SD = 4.3) were examined revealing no significant correlations between subjective and objective measures of imagery ability. Overall, objective imagery tasks were more strongly related to visuoperceptual, visuospatial, and constructional abilities compared to working memory tests with little or no relationship with subjective imagery measures. Similarly, Burton and Fogarty (2003) tested the factor structure of VI and spatial abilities by examining whether a primary imagery factor can be identified as a separate dimension of individual differences. To do so, 213 participants (99 males and 114 females) completed a test battery of 26 markers of cognitive ability; five self-report VI questionnaires, seven experimental imagery tasks, and two creative imagery tasks. Confirmatory factor analysis suggested that self-report measures of imagery ability can define separate dimensions of spatial ability if the stimuli used in self-report measures are close to that used in spatial tests. However, current self-report measures include different stimuli (e.g., recall of movement experience) to examine imagery ability leading to a weak relationship between subjectively and objectively derived measures.

Attempts to link self-report questionnaires and objective measures have failed to show a consistent and substantial relationship (Di Vesta et al., 1971; Ernest, 1977; Poltrock & Brown, 1984; Richardson, 1977) may be the results of: (1) using subjective measures with poor psychometric properties (i.e., non-effective criterion on which to base their ratings), (2) confounding components of imagery control, generation, and vividness, (3) subjective ratings of ability being unrelated to the accuracy with which one performs the actual manipulation, (4) not controlling the nature of the image generated or the strategies used to resolve objective tasks (Lequerica et al., 2002), and (5) the variability of time since experiencing the movement linked to memory decay. Furthermore, the nature of the instructions, including imagery perspective and mode as well as skill level should be taken into account.

Because of the aforementioned limitations, brain imaging measures that capture the “real-time” imagery experience of individuals have emerged. For example, Amedi et al. (2005) argued that the subjective experiences of VI and visual perception are different. Functional MRI demonstrated that each task (i.e., visual objective recognition and viewing scrambled images of the same objects) showed positive BOLD activation in visual brain regions in relation to scores on the VVIQ establishing that most brain areas activated during VI are also activated during visual perception of objects. These results are difficult to generalize to movement experiences relevant in the sport sciences because this study used a simple visual object recognition task making it difficult to relate to studies in the motor domain. In addition, perceiving objects do not require much filtering, and because the visual items in this study were so salient the mechanism that creates this deactivation was still unclear. Therefore, the recorded results may be due to less neuronal activity in “irrelevant” sensory areas during VI compared to visual perception or an active suppression process triggered by a separate brain region.

To our knowledge, Cui et al, (2007) have been the only researchers claiming that individual variability in imagery can be measured objectively. Eight participants first completed the VVIQ and then a visualization task (i.e., bench press or stair climbing) within an fMRI scanner in relation to a color-naming interference task. Results indicated that participants who reported being more visual in subjective and objective measures are more susceptible to a color-naming interference task suggesting that individual differences in VI vividness can be quantifiable without the use of subjective measures. However, participants either completed an upper or lower body task which has been shown to influence the consistency of activation within the general imagery networks (Hetu et al., 2013). While results such as these add insight into the “real-time” imagery experience, consistent evidence for validating self-report questionnaires is lacking.

Common self-report imagery ability questionnaires have been recently used as screening tools to determine the functional neuroanatomical networks activated between ME and MI. Early cognitive psychology research used EEG to investigate the topographical changes of brain activity accompanying VI and MI between good and poor imagers (Marks & Isaac, 1995). The VVIQ and VMIQ were used to select 16 participants based on their self-reported vivid or non-vivid imagery ability scores (eight highest and eight lowest scores) to complete both imagined and physical performance of a finger touching and fist clenching task. Data indicated that there were differences in the patterning of electrical activity responses between participants selected for their reports on vivid and non-vivid imagery which are consistent with previous findings and further confirm the construct validity of the VVIQ and VMIQ.

More recently, Williams et al. (2012) completed a similar study of Guillot et al. (2008, 2009) to determine the extent to which the vividness of a motor image is associated with the pattern and/or level of neural activation in motor related areas of the brain. The relationship between imagery ability and MEP amplitude following TMS during MI was examined in 15 participants (five males and 10 females) completing a mental rotation task during four conditions (i.e., static hand (baseline), movement observation, MI, and ME). Correlations between imagery ability and MEP amplitude revealed an inverse correlation with the scores on the kinesthetic components of the VMIQ-2 indicating that greater MEP amplitude is associated with more vivid and kinesthetic images, and that activation of the motor system during MI appears to be influence by imagery ability. Although research suggests that poor imagers may use different techniques to solve a task compared to good imagers (Logle, Pernet, Buonocore, & Della, 2001), an individual's self-reported ability to produce vivid images can reflect their ability to reproduce a vivid image of the task.

MI is currently considered a multi-dimensional construct (Guillot & Collet, 2008), and its underlying processes have recently been measured using a combination of psychometric tests, qualitative procedures, chronometric methods, and psychophysiological techniques. To improve upon using these techniques separately, a motor imagery index (MII) was developed to integrate certain aspects of the above measures into a single index of MI quality (Collet et al., 2011). It was hypothesized that an overall MII score can be calculated from six components: (1) self-estimation of image quality, (2) psychometric assessment of imagery vividness, (3) MC, and (4) three psychophysiological indices of imagery. Accordingly, each sub-indicator was calculated, weighted and summed to determine the final index of movement imagery ability for each individual; the greater the index, the better the imager.

The MII was recently used to screen participants as good or poor imagers in a study exploring the relationship between MI and change in corticomotor and intracortical excitability during MI (Lebon, Byblow, Collet, Guillot, & Stinear, 2012) indicating that greater corticomotor excitability during imagery was facilitated by MI compared to the listening only condition (control). Furthermore, good imagers experienced muscle-specific temporal modulation of corticomotor excitability, similar to that observed during ME whereas poor imagers only experienced a general increase in corticomotor excitability during MI that was not muscle specific. Although this study showed the reliability of the MII to separate participants based on MI ability and that it may more accurately describe participant's imagery ability, a thorough understanding of each tool and data processing method as well as having access to the equipment is needed.

Individual Differences that Moderate the Effectiveness of Imagery

Sport psychologists have examined various individual differences, factors referring to relatively stable traits or differences that exist between people in their subjective evaluations of the world, to explain imagery variations. These have been used in an effort to explain and/or predict the performance of participants in sport contexts, but they are also relevant in the study of imagery. Drawing from Paivio (1985), imagery is an ability that improves with practice, but its effectiveness on performance is contingent on specific individual characteristics such as gender (i.e., biological sex) handedness (i.e., asymmetry of hemispheric activation), and movement experience. These differences can influence the imagery system in working memory directly, in which athletes with good imagery ability may perform better in a competition than athletes with poor imagery skills because they are better able to imagine the upcoming performance. Therefore, it is important to discuss how these individual differences moderate imagery effectiveness.

Gender

Findings concerning gender have shown general trends throughout the sport and neuroscience literature. Galton (1883) originally proposed that females have better abilities of visualizing than males and that this ability increases with age in both genders. This has been confirmed by studies with females reporting more auditory imagery (Griffitts, 1927), color imagery (Palmer & Field, 1968), and visual imagery (Campos & Perez, 1988; Durndell & Wetherick, 1975; Harshman & Paivio, 1987; Narchal & Broota, 1988; Paivio & Harshman, 1983). Additional studies show that females also report more vivid visual imagery using the Betts' Questionnaire upon Mental Imagery (Sheehan, 1967; White, Ashton, Brown, 1977) and the VVIQ (Campos & Sueiro, 1993; McKelvie, 1986), as well as more vivid movement imagery using the VMIQ (Campos & Perez, 1988).

Studies finding females to have better imagery ability compared to males have used self-report measurements (Campos & Perez, 1988; Durndell & Wetherick, 1975; Harshman & Paivio, 1987; Narchal & Broota, 1988; Paivio & Harshman, 1983). For example, in a sample of 51 male and 82 female undergraduate students that completed the VMIQ Campos and Perez (1988) showed that females reported significantly greater vividness of movement imagery than men which corroborate with previous investigations (Ashton & White, 1980; Sheehan, 1967; White et al., 1977). Similar results were found in an additional investigation of 289 participants (134 males and 155 females) of various age groups who completed the VVIQ indicating that visual imagery vividness is significantly influenced by gender, $F(1, 283) = 6.905$, $p < 0.05$, in all age groups (Campos & Sueiro, 1993). Furthermore, Isaac and Marks (1994) investigated individual differences in imagery experiences and compared the differences in the VVIQ and VMIQ distributions obtained from 345 children and 202 adults. Overall, females reported more vivid imagery on both questionnaires, substantiating earlier findings. Results indicating that females have better imaginal processes may be explained by their superior in free and incidental learning (Sheehan, 1971) and the ability to recall picture details (Marks, 1973).

Although earlier work investigating gender differences indicates females to have better imagery ability, it has been rivaled by others showing that males have better visual imagery (e.g., Christiansen, 1969), a greater variety of form imagery, and auditory imagery (White et al., 1977). More recent studies have found gender differences in spatial abilities and in sensory integration (Berthoz & Viaud-Delmon, 1999; Campos, Perez-Fabello, & Gomez-Juncal, 2004), particularly with mental rotation tests (the ability to rotate mental representations of objects) showing male performance advantages (Parsons et al., 2004; Siegel-Hinson & McKeever, 2002). For example, in a sample of 129 participants (60 males and 69 females) Campos et al. (2004) investigated gender differences in performance-assessed and self-reported imaging capacity showing that males obtained higher scores than females on performance-based tests (i.e., visuospatial ability scores); however, no gender differences existed for imagery control. Similar studies also indicated that males responded more quickly with fewer error rates when rotating objects (Rilea, 2008) as well as the ability to preserve the temporal organization of movement during mental practice (Hoyek, Champely, Collet, Fargier, & Guillot, 2009) and ease of movement imagery (Monsma et al., 2009; Williams et al., 2011).

Despite certain studies showing gender differences, others have found no significant gender differences in the imagery experience (Ashton & White, 1980; Beech & Leslie, 1978; Campos & Perez, 1988; Lane, 1977; McConkey & Nogrady, 1986), even expressing that gender differences are unimportant to examine (Di Vesta, Ingersoll, & Sunshine, 1971). For example, in a sample of 60 participants (24 males and 34 females) Parsons et al. (2004) explored the relationship between mental rotation tasks in a virtual environment and other neuropsychological measures according to gender differences. Results are contradictory because they showed significant gender differences favoring males (t (42) = -3.27; p = 0.002) on a paper-and-pencil version of the mental rotation test, but no differences were found between males and females on duration (t (20) = -0.18; p = 0.86) or efficiency (t (20) = 0.37; p = 0.72) of the virtual reality spatial rotation test. A mental rotation paradigm was also used by Seurinck, Vingerhoets, de Lange, and Achten (2004) to examine gender specific cortical activation patterns of 22 right-handed participants (11 males and 11 females) during the mental rotation of hands and tools. Imaging data revealed a common cortical activation pattern for males and females including the superior frontal lobe, middle frontal gyrus, and extrastriate occipital areas indicating that both genders use similar motor strategies during mental rotation tasks.

Recent studies continue to show non-significant differences between genders. For example, in a study of 56 participants (28 females and 28 males), Callow and Hardy (2004) did not find any significant differences in imagery ability between males and females on any of the MIQ or VMIQ scales and totals which is contradictory to previous research indicating females self-reporting better imagery ability (Campos & Perez, 1988; Campos & Sueiro, 1993; McKelvie, 1986; Sheehan, 1967; White et al., 1977). Likewise, gender differences were not found in MIQ-R score ($t = 0.7$, $p > 0.05$), mental chronometry ($t = -0.82$, $p > 0.05$), auto-estimation score ($t=0.6$, $p > 0.05$), ANS activity ($t=0.07$, $p > 0.05$), global imagery score ($t=0.6$, $p> 0.05$), expertise (Guillot et al., 2008), imagery perspective ($p > 0.05$), motor threshold, MEP latencies and amplitudes, central conduction time (Livingston, Goodkin, & Ingersoll, 2010), muscle responses (Guillot et al., 2007), or VI versus KI (Guillot et al., 2009). Overall, imagery has long been considered in both sport psychology and neuroscience and differences in theoretical assumptions and measurement paradigms may explain equivocal findings. Given these inconsistencies, the present study will only use female participants to decrease the possibility of gender playing a role in brain activity differences.

Handedness

Handedness is considered an important example of hemispheric specialization in humans (Serrien et al., 2006), making it paramount to control investigations of neurological activity during MI because brain activity in the cortices, gyri, and sulci differs depending on the dominant hand (Hammond, 2002; Rademacher et al., 2001). Handedness can either refer to hand preference or the asymmetrical performance of a task (Triggs, Calvanio, Levine, Heaton, & Heilman, 2000). There has been a strong interest in handed because of how it can impact brain function when completing a task (Corballis, 2003; Grabowska, Herman, Nowicka, Szatkowska, & Szelag, 1994).

Brain mapping studies using fMRI and PET have attempted to identify neuronal underpinnings by comparing movement related activity during finger and/or hand movements in right- and left-handers (Lutz et al., 2005; Siebner et al., 2002; Solodkin et al., 2001). These studies focused on differences in lateralization of movement related activity in different areas of the brain including the amygdala, hippocampus, primary sensorimotor cortex, SMA, PMC, and M1 (Dassonville et al., 1997; Herve et al., 2006; Kim et al., 1993; Siebner et al., 2002; Solodkin et al., 2001; Szabo, Xiong, Lancaster, Rainey, & Fox, 2001) suggesting that brain asymmetry may occur because of hemispheric lateralization of the cortical areas directing motor function. Evidence has illustrated handedness related structural and functional asymmetries of simple motor tasks (Baraldi et al., 1999; Hammond, 2002; Rademacher et al., 2001). For example, in a sample of 10 right-handed male participants completing a sequential finger-to-thumb opposition with the right or left hand Baraldi et al. (1999) showed that only movement of the contralateral hand was found to be equally distributed in the left and right perirolandic cortex (including the PMC of the dominant hemisphere), while ipsilateral finger movements did not show any significantly activated brain areas. However, other studies using more complex motor tasks show that the degree of asymmetry decreases with task difficulty (Hausmann, Kirk, & Corballis, 2004) or the effect of handedness was found in other brain areas (i.e., SMA, PMC) (Babiloni et al., 2003; Siebner et al., 2002; Solodkin et al., 2001). These results indicate that the nature of the task (i.e., force, speed, and accuracy) as well as age and gender (Kumar & Mandal, 2003) interact with handedness and alter motor activation patterns in the brain.

In addition, research on lateralized neuronal activity has not revealed a clear pattern of association and the affect handedness has on brain activity (Fischer, 2005; Livingston et al., 2010; Szabo et al., 2001). For example, in a sample of 20 right-handed and 17-left handed participants completing a 10-item handedness questionnaire (drawn from the Edinburgh Laterality Inventory and Reitan Handedness Scale), Sazabo et al. (2001) compared the amygdalar and hippocampal volume ratios between right- and left-handed participants during fMRI. Results showed significant differences for volume ratios between right- and left-handed participants with the amygdala and hippocampus volumes significantly larger on the right side than on the left for right-handed participants, while the left-handed group did not show a significant difference between right- and left-sided structures. Subsequently, with a sample of 16 males and 16 females de Gennaro et al. (2004) conducted a TMS study examining the asymmetry of corticospinal excitability by recording the MEPs of the abductor digiti minimi muscles in both hands. Before completing the TMS protocol hand preference was measured by a standard handedness questionnaire with 16 (eight males and eight females) right-handed participants and 16 (eight males and eight females) left-handed participants. Results indicated that motor thresholds of right-handed participants were lower than left-handed participants; specifically, MEP amplitudes of right-handed participants were significantly greater for the right hand, and left-handed participants showed greater MEPs for the left hand. Because of the debate of cortical motor activation during finger/hand movements, Kloppel et al. (2007) examined the impact of hand preference on neuronal activity in the PMC of 16 right-handed and 16 left-handed participants. Data from event-related fMRI revealed a relative increase in activity in the dorsal PMC and right primary sensorimotor cortex in right-handed participants compared to left-handed participants indicating that handedness is associated with differences in motor control of movement tasks. Altogether, results indicate that the cortical component of the motor system is, to an extent, based on hand preference.

More recent research has measured the effect of hand preference according to reaction time within mental rotation paradigms (Choisdealbha, Brady, & Maguinness, 2011; Takeda, Shimoda, Sato, Ogano, & Kato, 2010), as well as the difference in brain organization of left and right handed individuals (Grabowska et al., 2012). For example, in a sample of 16 right-handed males and 15 left-handed males (assessed by the Edinburgh Handedness Inventory) Takeda et al. (2010) used a mental rotation task to show that right-handed participants responded faster to a right hand picture than a left hand, whereas no significant difference was seen for left-handed participants suggesting that this difference depends on a laterality balance of hand motor skills. In addition, a sample of 52 participants (24 males and 28 females) completed an fMRI experimental paradigm consisting of a simple (flexion/extension of the index finger) and complex (sequential opposition of the thumb to the other finger) movement task to examine the brain organization of motor control in right- and left-handers (Grabowska et al., 2012). Results showed that both right- and left-handers' movements of the preferred hand activated the contralateral hemisphere, whereas a balanced pattern was found for the non-preferred hand suggesting that the preferred hand is controlled mainly by the hemisphere contralateral to that hand.

The aforementioned studies continue to show that handedness alters brain activation during motor tasks, particularly that the contralateral hemisphere is activated according to hand preference. However, there were no studies found examining the changes in the brain when participants are asked to complete a task with their right hand versus their left hand, which may prove to be an important methodological paradigm. In order for handedness to not be a confounding factor, only right-handed individuals will be included.

Movement Experience

Movement experience, or expertise, refers to the ability to maintain a given skill level under a variety of environmental conditions (see Fairweather, 1999; Fitts & Posner, 1973). Overall, imagery significantly helps performance of both novice and experienced athletes, but the effects of imagery are stronger with higher competitive athletes or those with more experience compared to lower level athletes or those with less experience (Calmels et al., 2004; Cumming & Hall, 2002; Gregg et al., 2005). For example, in a sample of 150 athletes (78 males and 72 females) of varying experience levels Cumming & Hall (2002) showed that higher level athletes perceived imagery to be more relevant to performance and reported using it more frequently compared to recreational athletes. This is because experienced athletes tend to have more effective strategies when inspecting a particular visual display (Adams, 1987), as well as having more refined knowledge bases and effective utilization of information compared to novices which alters the neural mechanisms during imagery. Understanding the relationship between experience and imagery is important whenever measuring imagery ability.

Researchers have commonly examined the effects of experience on MI by comparing novice and expert athletes (Milton, Small, & Solodkin, 2004; Milton, Solodkin, Hlustik, & Small, 2007; Ross, Thach, Ruggieri, Lieber, & Lapresto, 2003) and performers (Kleber, Birbaumer, Veit, Trevorrow, & Lotze, 2007). Comparisons have shown differences between novices and expert athletes completing self-report questionnaires (e.g., McAvinue & Robertson, 2007; Morris et al., 2005) and a variety of prospective judgments (e.g., Ouchi et al., 2005), as well as mental rotation and motor simulation paradigms (Frak et al., 2001; Johnson, 2000; Shepard & Metzler, 1971). For example, during single photon emission computerized tomography Charlot, Tzourio, Zilbovicius, Mazoyer, & Denis (1992) showed expertise related differences in a mental scanning paradigm in which significant increases in blood flow were found in the left temporo-occipital cortex of good visuospatial imagers compared to poor visuospatial imagers. In addition, in a sample of eight right-handed male professional chess players and six (four males and two females) amateur chess players activation was found in the precuneus and cerebellum for professionals, while the premotor and parieto-occipital cortices were activated in the amateurs supporting the idea that the cerebellum and precuneus play a large role in imagery processing judgments.

Modern brain imaging techniques (i.e., PET and fMRI) allow researchers to identify neural substrates that can be related to motor skill learning and the functional changes seen during acquisition (e.g., Karni, 1996) and motor sequence learning (Grafton et al., 1996; Hazeltine, Grafton, & Ivry, 1997; Lafleur et al., 2002; Floyer-Lea & Matthews, 2005). For example, in a sample of eight right-handed professional violinists (six males and two females) and eight right-handed amateurs (two males and six females) Lotze, Scheler, Tan, Braun, and Birbaumer (2003) found less neural activation in professional violinists compared to amateur violinists during the physical execution and imagery of a musical task. Similar results were found in pianists demonstrating decreased activation in the motor cortex (i.e., SMA, PMC, and ipsilateral M1) implying an economy of effort (i.e., reduced recruitment of motor association areas) for professional musicians (Haslinger et al., 2004; Hund-Georgiadis, & von Cramon, 1999; Krings et al., 2000).

Studies have also shown that neural networks activated by the execution of a movement differ as a function of the level of experience (Lacourse et al., 2005; Milton et al., 2007; Ross et al., 2003). For example, six male golfers of various handicaps completed a brain mapping study comparing a golf swing using IVI illustrating an inverse relationship between brain activity and skill level; decreased activations occurred with increased skill level, especially in the SMA and cerebellum (Ross et al., 2003). Similar results were found in 54 participants (19 males and 35 females) completing the MIQ

(Mean = 22.6, SD = 4.9), the VMIQ (Mean = 94.3, SD = 24.2), and a subsequent sequential button press task inside a scanner before (novel) and after (skilled) a week of intensive physical practice (Lacourse et al., 2005). MRI results revealed congruent brain activations associated with ME and MI in both the novel and skilled phases of learning (i.e., similar clusters in M1, ventral PMC, primary somatosensory cortex, and SMA). Although both studies demonstrate congruent activation between novel and skilled individuals, the novel phase showed more extensive activations compared to the skilled phase. It was later reported that brain regions activated in novices but not experienced individuals are involved in motor planning in the initial phases of learning (Milton et al., 2007).

More recently, Wei and Luo (2010) examined 12 (six males and six females) sport experts (divers) and 12 (six males and six females) novices during imagery of professional motor skills and simple motor skills. Functional MRI data indicated that sport experts revealed a specific, focused cerebral activity pattern found in experience-related motor tasks compared to novices, which may indicate that they are able to use a higher order of motor control during MI. Chang et al. (2011) also completed an fMRI study comparing the activation maps of 18 elite archers (six males and 12 females) and 18 non-archers (eight males and 10 females) during the mental rehearsal of archery. Elite archers showed activation in the supplementary motor areas, while non-archers showed activation in the premotor and supplementary motor areas, inferior frontal region, basal ganglia, and cerebellum indicating that additional brain areas are activated when learning an unfamiliar task. These findings indicate a relative economy of effort in the cortical processes of elite individuals requiring less energy to execute which may account for their enhanced motor performance. Together, these data support differences between the neural mechanisms activated by novices and experts during imagery, as a function of the individual movement experience. In order to address this difference, normal, college-aged female students will be targeted to participate.

Limitations of the Literature

There is a methodological assumption that imagery is generated by the same mechanisms as those that sub-serve perception, but efforts to measure the actual formation of vivid and accurate images as well as relate subjective and objective measures of imagery have produced unfavorable results. Despite cumulative findings that IA impacts motivational and cognitive functions, as well as the learning and performance of individuals, one major limitation still exists: the bulk of what we know about imagery measurement, especially in the sport science literature, rests on various self-report inventories (i.e., MIQ and VMIQ). This is problematic because the psychometric validation of imagery has not been measured using objective measures concurrently while participants are engaged in imagery. This is despite using advanced technology for other purposes such as investigating the topical changes of brain activity accompanying VI and MI between good and poor imagers, and determining whether the vividness of a motor image is associated with the pattern of neural activation in motor related areas of the brain. If the major purposes of imagery research are to discern *why* individuals are using imagery and *what* they are imaging, it is imperative to use instruments intended to measure target characteristics (i.e., perspective, imagery ability, and vividness) and how this is connected to neural activity. If current technologies, which enable the observation of neural activity, do not show a consistent relationship with the concurrent mental simulation of movement, then the concurrent validity cannot be established and we cannot be confident that self-report questionnaires actually capture the imagery construct. One way to do this has been to use neurophysiological measures (i.e., PET and fMRI) to measure brain activity of vivid and accurate mental images experienced by participants screened for MI ability. However, research has indicated that it is inappropriate to equate results from subjective measures to objective measures of IA (e.g., Moreau et al., 2010), and that imagery ability scores may not correctly classify imagery ability groups (e.g., van der Meulen et al., 2012). Therefore, the convergent validity between like scales as well as the discriminant validity between different scales of current self-report imagery questionnaires (i.e., MIQ-3 and VMIQ-2) should be examined to further validate their use.

Statement of Purpose

The purpose of this research study was twofold: (1) to help extend the present theories of motor imagery by examining if imagery ability measured subjectively and objectively converge to indicate that brain activity corresponds to self-report imagery ability, and (2) to extend the construct validity of two commonly used self-report IA questionnaires. The present study was devised to examine whether a group of healthy participants screened as having good or poor imagery abilities recruited comparable or distinct brain activity during each of three conditions (i.e., KI, IVI, and EVI); brain activity was measured while participants were instructed to, and purported to mentally perform an upper extremity movement. Accordingly, we cross-validated self-report and neural measures by comparing the BOLD signal using fMRI technology of participants screened as having good or poor IA using a cluster analysis to classify participants examining correlations between like scales for convergent validity as well as between different scales for discriminant validity. To this end, the following research aims will be addressed:

Research Aim #1: Isolate the common/core neural network that is activated during motor imagery (in general) in contrast to a control (rest) condition.

H_1: There may be a common neural network that is activated by all of the imagery types to a control condition (i.e., supplementary motor area, premotor cortex, and primary motor cortex).

Research Aim #2: Isolate differences in neural activation between the three types of motor imagery (EVI, IVI, and KI).

H_1: External visual imagery will elicit greater activity in the ventral visual stream (ventrolateral occipito temporal cortex, inferior parietal cortex, precuneus, posterior cingulate, and frontopolar cortex) when compared directly to IVI.

H_2: Internal visual imagery will elicit greater activity in the dorsal visual stream (inferior parietal and somatosensory cortex) when directly compared to EVI.

H_3: Both visual imagery conditions will elicit greater activity in the posterior lateral premotor cortex, occipital activations (primary visual cortex, secondary visual cortex, and associative visual cortex), superior parietal regions (somatosensory cortex, PMC, and SMA), and posterior inferior parietal lobe when compared to the KI condition.

H_4: Kinesthetic imagery will elicit greater activity in the superior lateral premotor cortex, anterior and posterior parts of the SMA, lateral and anterior parts of the inferior parietal lobe, frontal areas (dorsolateral prefrontal cortex, ventral anterior cingulate cortex, inferior frontal areas (pars opercularis), basal ganglia (putamen and caudate nucleus)), and cerebellum when compared to the VI conditions.

Research Aim #3: Explore the biological validity of the MIQ-3, determining if participants classified as having good versus poor imagery ability, using a self-report measure, can be differentiated based on the BOLD signal while engaged in imagery.

H_1: During IVI, participants classified as having good IVI imagery ability will show more activity (increased intensity) in the dorsal visual stream (inferior parietal and somatosensory cortex), as well as the posterior lateral premotor cortex, occipital activations (primary visual cortex, secondary visual cortex, and associative visual cortex), superior parietal regions (somatosensory cortex, PMC, and SMA), and posterior inferior parietal lobe when compared to those classified as having poor IVI ability.

H_2: During EVI, participants classified as having good EVI imagery ability will show more activity (increased intensity) in the ventral visual stream (ventrolateral occipito temporal cortex, inferior parietal cortex, precuneus, posterior cingulate, and frontopolar cortex), as well as the posterior lateral premotor cortex, occipital activations (primary visual cortex, secondary visual cortex, and associative visual cortex), superior parietal regions (somatosensory cortex, PMC, and SMA), and posterior inferior parietal lobe compared to those classified as having poor EVI ability.

H_3: During KI, participants classified as having good KI imagery ability will show more activation (increased intensity) in the superior lateral premotor cortex, anterior and posterior parts of the SMA, lateral and anterior parts of the inferior parietal lobe, frontal areas (dorsolateral prefrontal cortex, ventral anterior cingulate cortex, inferior frontal areas (pars opercularis), basal ganglia (putamen and caudate nucleus)), and cerebellum compared to those classified as having poor KI ability.

Research Aim #4: Examine the convergent validity between like scales (EVI, IVI, and KI) of the MIQ-3 and VMIQ-2.

H_1: There will be significant moderate to high ($r \geq 0.50$) positive correlations between like subscales of the MIQ-3 and VMIQ-2.

H_2: There will be lower correlations between unlike subscales of the MIQ-3 and VMIQ-2.

H_3: The VMIQ-2 subscale scores and BOLD signals of good and poor imagers grouped by MIQ-3 scores will be significantly different.

Data from the present study illustrated the “real-time” imagery experience of participants, and also provided data to validate that participants were actually engaging in the indicated imagery condition while completing a task from a self-report imagery ability questionnaire affirming the practicality of questionnaire-based imagery assessments.

CHAPTER 2: JOURNAL ARTICLE 1

BIOLOGICAL EVIDENCE FOR INTRA-INDIVIDUAL DIFFERENCES IN MOVEMENT IMAGERY ABILITIES[1]

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[1] Seiler, B. S., Monsma, E., & Newman-Norlund, R. To be submitted to *Journal of Sport and Exercise Psychology*.

Imagery research remains a prominent topic as theoretical models such as the Applied Model of Mental Imagery (Martin, Moritz & Hall, 1999), PETTLEP (Holmes & Collins, 2001) and MIIMS (Guillot & Collet, 2008) are serving the movement sciences with an ultimate goal of discovering precise imagery prescriptions in sport, dance, exercise and rehabilitation contexts. The effectiveness of using imagery as a performance enhancing strategy depends upon one's capacity to generate images. Images are reformed or constructed anew from information stored in long-term memory and can include emotive properties along with those that are motor. Motor imagery (MI) involves deliberate cognitive simulation or rehearsal of an action without engaging in overt physical movements (Moran et al., 2012; Olsson & Nyberg, 2010). Studies have shown MI is an ability that improves with practice (e.g., Goss, Hall, Buckolz & Fishburne, 1986), and according to Paivio (1985) it is a function of experience interacting with genetic (biological) variability. That is, efficiency in recruiting neural networks (i.e., when more than one area/region is consistently activated) during imagery translates to perceived ease, vividness and/or controllability of generating images or, *imagery ability.* Studies affirm that imagery abilities are not universal across individuals. Rather, an individual may have varying capacities to generate images depending on imagery mode (Goss et al., 1986; Guillot, Collet, Nguyen, Malouin, Richards & Doyon, 2009) and/or perspective (Williams, Cumming, Ntoumanis, Nordin-Bates, Ramsey & Hall, 2012).

Visual (e.g., what an individual sees) and kinesthetic (i.e., sensation of what an image feels like) are the two most common sensory modes used for generating images.

When visual images are generated, they are either seen from the first-person perspective (i.e., image viewed through one's own eyes) or the third-person perspective (i.e., image viewed from an observer's standpoint, such as on a video or as part of the audience) (Callow et al., 2013). In both the behavioral and neural sciences, these imagery modes and perspectives are typically assessed using the Movement Imagery Questionnaire (MIQ: Hall, Pongrac, & Buckholz, 1985), now in its second revision (MIQ-3: Williams et al., 2012) or the Vividness of Imagery Ability Questionnaire (VMIQ: Isaac, Marks, & Russell, 1986) also revised (VMIQ-2: Roberts, Callow, Hardy, Markland, & Bringer, 2008). Both instruments measure visual (VI) and kinesthetic imagery (KI) abilities and the modifications include separation of the visual scale into internal (IVI) and external (EVI) perspectives. Internal validity of these constructs accumulated over time and iterations. For example, Hall and Martin (1997) reduced the number of movements from nine to four (i.e., items) and inversed the scale so that higher scores represented better abilities. This is in contrast to the VMIQ-2 which is comprised of 12 movements and higher scores are anchored as poorer vividness and clarity. Notably, and aligned with Richardson's (1995) assertions of gender differences in imagery ability, Monsma et al. (2009) demonstrated through traditional confirmatory factor analysis that the visual and kinesthetic model fit better for females than males. This was not the case in the recent Multitrait-Multimethod (MTMM) analyses of the MIQ-3 which accounts for the common variance related to applying the same four movements when assessing each imagery ability; gender invariance of the three constructs was demonstrated using this method (Williams et al., 2012).

With evolutionary technology, imagery researchers are actualizing Paivio’s idea that there is a biological basis to inter- and intra-individual differences in imagery abilities. Mental chronometric (see Guillot & Collet, 2005) and neurological studies (see Guillot et al., 2008; 2009) have long supported the congruence, or theoretically the functional equivalence (Homes & Collins, 2001) between physical movement and MI of that movement, but recently researchers have embarked on validating MI ability assessments with neurological data (Guillot et al., 2008; 2009; Jiang et al., in press). This line of research is particularly relevant because a central tenet of theoretical models, such as Martin, Moritz & Hall’s (1999) Applied Model of Mental Imagery, is that individuals having greater capacities to generate MI will experience greater learning and performance-related benefits; imagery ability mediates and moderates the relationship between what is imaged and the intended learning, performance or rehabilitation outcomes. Accordingly, Cumming and Williams’ (2013) recently introduced the Revised Applied Model of Deliberate Imagery Use for Sport, Dance, Exercise and Rehabilitation. A seminal extension of the model was inclusion of personally meaningful reasons for using various types of imagery while maintaining the importance of imagery ability as originally proposed by Martin et al. (1999). Interestingly, the revised model explains that imagery characteristics such as mode and perspective are influenced *by* imagery ability. This is counter to sport and neuroscience conceptualizations and particularly assessments of imagery indicating intra-individual differences in the measured characteristics, like VI and KI modes or internal (IVI) and external (EVI) perspectives. If these imagery characteristics are represented on imagery ability scales and are each distinguishable by neural network activity, then mode and perspective distinctions are imagery abilities in and of themselves. This is of course demonstrated through intra-individual differences in MIQ scores particularly in intervention studies where participants are screened into one of four groups based on reporting 1) good visual and poor kinesthetic and albeit unusually, even 2) poor visual and good kinesthetic abilities in addition to those reporting 3) good and 4) poor scores for both scales (Abma, Fry, Li & Relyea, 2002; Goss et al., 1986). Moreover, through imagery intervention Rogers, Hall, and Barr (1991) demonstrated imagery abilities improve with practice.

In addition to the psychometric and behavioral evidence supporting intra-individual differences in imagery abilities, interestingly, neuroscience studies have actually driven mode and perspective distinctions of the MIQ-3 (see Williams et al., 2012), but studies have not yet examined the biological validity of this popular instrument directly. Within the neurological paradigm, fMRI technology measures the blood oxygenation level-dependent (BOLD) signal in specific brain areas during real-time imagery enabling the isolation of areas, within areas representing neural networks that are active and associated with the instructions to use a specified imagery ability (i.e., KI, IVI, or EVI). Using the cognitive subtraction method (Peterson et al., 1989), which involves comparing two conditions that are presumed to differ in in only one discrete feature, enables isolation of peak activation areas while participants are engaged in imagery, thus, biologically representing imagery ability. Neurological explanations are important to advance models driving the sport science literature. Simulation theory for examples predicts an overlap of brain activity for physically performing and imagining the same movement (Jeannerod, 2001). Therefore, if brain activity is mapped as different in location and intensity when mode or perspectives are compared while participants are instructed and purport to be using a particular imagery ability, not only is this biological evidence of construct validity but also representative of intra-individual differences in imagery abilities.

Initial fMRI investigations demonstrated real-time visual and kinesthetic imagery recruit some common (e.g., connection from the superior parietal lobule to the SMA) but also different neural substrates in finger (Binkofski et al., 2000) and hand (Solodkin et al., 2004) movement tasks where VI is represented by peak activity in visual areas such as areas between the occipital cortex and parietal lobule (posterior intraparietal sulcus) and KI by activity in motor-related areas which are more anterior. Although these pioneering studies elucidated neural networks involved during visual and kinesthetic imagery, there were important methodological limitations including: 1) participants were not screened as having superior imagery abilities, 2) manipulation checks to control the quality of imagery during data collection were overlooked (Binkofski et al., 2000; Solodkin et al., 2004) and 3) a cross sectional design was used where participants were either assigned to a visual or kinesthetic imagery group (Solodkin et al., 2004), precluding intra-individual comparisons.

To address these limitations, Guillot et al. (2009) devised a global imagery score inclusive of an aggregated MIQ-3 score, mental chronometry and a physiological measure (i.e., skin resistance) to screen good imagery ability participants into their study. They also used a within subjects design where visual neural activity was compared to kinesthetic activity in the same participants in addition to comparing activity while physically performing the imaged task. Among these good imagery ability participants, neural network activations for imagined compared to physically performed movements were similar, further supporting the functional equivalence theory. Moreover, when visual and kinesthetic neural networks were compared, results indicated divergent networks; VI activated occipital areas and the superior parietal lobules while motor cortex and inferior parietal lobules were activated during KI. This ground breaking biological evidence for intra-individual variability in neural networks associated with two different imagery modes led researchers to question whether other imagery abilities could be further differentiated.

Jiang et al. (in press) recently extended the external validity of KI and VI inferred through imagery during a finger tapping task by asking participants to image one of the VMIQ-2 gross motor movements that was involved in screening for good imagery ability participants. Using fMRI to identify and distinguish neural networks used during imagery modes and perspectives (KI, IVI, and EVI), results indicated that each imagery ability involved independent processes making them distinguishable from each other. Specifically, KI activated a large amount of subcortical areas in the cerebellum and areas in the inferior frontal cortex, IVI activated more of the parietal lobule, and interestingly, EVI activated the temporal cortex. While most of the results accurately mapped respective brain areas expected to be associated with kinesthetic and visual imagery abilities, the temporal cortex activity during EVI was irrelevant to MI and likely associated with perceiving the spatial elements off the instruction screen.

A common limitation of both these latter studies is the type of movement imagined during fMRI scanning. While finger tapping was ecologically valid (i.e., the movement could be done while inside the scanner) it lacks relevance to gross motor tasks which were the basis of the imagery screening tool and are more relevant to sport settings. In contrast, although the imagery task chosen in the Jiang et al. (in press) study was directly part of the imagery ability screening instrument, the temporal distance between experiencing the VMIQ-2 movements in general, may have also confounded the findings. Additionally, because visual and kinesthetic scores were aggregated, it is unknown whether those with better abilities in one mode over another had more efficient neural networks when engaged in imagery and physical practice of a finger tapping task. Despite the accumulating biological evidence supporting within subject neural network differences for imagery modes (Guillot et al., 2009; 1998; Solodkin et al., 2004) and perspectives (Jackson et al., 2006; Kosslyn et al., 2001; Thompson & Kosslyn, 2000), studies have yet to examine intra-individual differences in neural networks involved in imagining any of the MIQ movements while using KI, IVI, and EVI MI abilities.

The purpose of this study was to examine the construct validity of the MIQ-3. To this end, we first considered the relationships between the MIQ-3 and VMIQ-2 scales. It was hypothesized that similar imagery ability scales would be related but not indicative of multicolinearity (i.e., $r > .90$), and that relationships between other paired imagery ability scales would be lower than those that are alike. In addition, we examined the construct validity of the MIQ-3 through fMRI by comparing the neural activity with specific imagery abilities (i.e., KI, IVI, and EVI) while engaged in a selected MIQ-3 movement. Consistent with functional equivalence of neural networks and previous research (Binkofski et al., 2000; Guillot et al., 2008, 2009; Jiang et al., in press; Solodkin et al., 2004) we expected KI to activate motor-related areas, IVI to activate the parietal lobule, and EVI to activate occipital areas and the temporal lobe. Next, applying the tenets of simulation theory (Jeannerod, 2001) our second aim was to isolate the common neural network across all imagery abilities while engaged in a selected MIQ-3 movement. Consistent with previous literature (e.g., Guillot et al., 2009; Halpern & Zatorre, 1999; Jiang et al., in press; Munzert, Zentgraf, Stark, & Vaitl, 2008; Sharma, Jones, Carpenter, & Baron, 2008), it was hypothesized that the SMA, PMC, and M1 would be more active during imagery than at rest. Intra-individual differences in neural activation during KI, IVI, and EVI were then considered. It was hypothesized that: (1) KI would elicit greater activity in the motor-related neural pathways (i.e., premotor cortex, SMA, inferior parietal lobule, frontal areas) and subcortical areas) when compared to VI, (2) IVI would elicit greater activity in the dorsal visual stream compared to EVI, (3) EVI would elicit greater brain activity in the ventral visual stream compared to IVI, and (4) both EVI and IVI would elicit greater activity in the visual neural pathways (i.e., premotor cortex, occipital cortices, superior parietal areas, and inferior parietal lobule) when compared to KI.

Method

Participants

From an initial screening of 206 participants, 18 healthy, female participants between 18 and 30 years of age (Mean age = 23.72 ± 2.42), screened as having good imagery abilities were selected for the study. Participants were 15 non-Hispanic White Americans, one Black/African American, one Hispanic/Hispanic American, and one Asian/Asian American. Their highest education level was high school diploma (n = 5), undergraduate degree (n = 10), and master's degree (n = 3). Participants' sport history varied (e.g., basketball, soccer, gymnastics, lacrosse, and rugby), while two participants did not report any. All participants were screened as right-handed (Edinburgh Handedness Inventory (EHI) Mean = 94.17 ± 9.26), had normal or corrected-to-normal vision, self-reported no history of neurological or psychiatric disorders and were not taking any medications.

Imagery Assessments

Movement Imagery Questionnaire-3 (MIQ-3: Williams et al., 2011). The 12-item MIQ-3 measures the self-reported ease or difficulty of generating images of four separate movements (arm rotation, jump, knee lift and toe touch) each along three scales: kinesthetic imagery (KI), internal visual imagery (IVI) and external visual imagery (EVI). Item completion involves physically performing each movement, imagining oneself performing the movement, then rating the ease or difficulty of imaging each movement on a 7-point Likert-scale where 1 = very hard to see/feel and 7 = very easy to see/feel. Subscale scores for the MIQ-3 range from 4-28 where higher scores represent better imagery ability. The MIQ-3 displays adequate internal consistency ($\alpha > 0.69$) and concurrent validity with the VMIQ-2 (Williams et al., 2011). In the present study (n = 206), alpha coefficients were: KI = 0.87, IVI = 0.83, and EVI = 0.88 with moderate inter-scale correlations (KI versus EVI: $r = 0.36$; KI versus IVI: $r = 0.52$ and EVI versus IVI: $r = 0.56$, $p < 0.01$).

Vividness of Movement Imagery Questionnaire-2 (VMIQ-2: Roberts et al., 2008). The VMIQ-2 assesses self-reported imagery vividness (i.e., clarity and realism) and is comprised of 12 motor tasks (e.g., walking, running, jumping sideways) for each of the three subscales: KI, EVI, and IVI. Participants record a score based on the clarity associated with representing each movement mentally using a 5-point Likert-scale from 1 (perfectly clear and vivid) to 5 (no image at all, you only know that you are “thinking” of the skill). In the present study, the VMIQ-2 scale was inversed to be consistent with the MIQ-3 where lower scores represented poor imagery ability and higher scores represented good imagery ability; subscales range from 12-60. Consistent with previous research (Williams et al., 2011, 2012) the internal consistencies of the VMIQ-2 scales in the present study were: KI = 0.95; IVI = 0.94 and EVI = 0.94. Inter-scale correlations were also moderate (KI versus EVI: $r = 0.39$; KI versus IVI: $r = 0.56$ and EVI versus IVI: $r = 0.65$).

Manipulation Check. To assess the extent participants followed the study protocol, participants completed a post-experiment debriefing questionnaire where they were asked to rate the extent they were able to focus on each imagery perspective or modality during the scan, whether they switched between imagery perspectives or imagery modalities, and the extent they were able to focus on the MIQ-3 protocol (i.e., arm movement) on a 10-point scale (1 = not at all to 10 = greatly).

Mental Chronometry

Based on the premise that imagery is under voluntary control (Sharma et al., 2008), mental chronometry was used as a manipulation check for temporal congruence between physical movement and imagery of that movement. Consistent with previous work (Collet et al., 2011; Malouin et al., 2008), participants were asked to physically perform and imagine the arm rotation task (Figure 2.1) along each of the MIQ-3 imagery abilities repeatedly for 30 seconds at a personally comfortable cadence. Participants followed audible prompts on a computer screen to begin and end each trial. The number of MIQ-3 arm rotation movements physically performed over 30 seconds was recorded followed by recording the number of KI, IVI and EVI self-reported repetitions performed while in an fMRI simulation scanner. Physical and imaged repetitions of the MIQ-3 arm rotation protocol were averaged across the three trials.

Electromyography (EMG)

Aligned with previous recommendations (Guillot et al., 2009) to record muscular inactivity during MI to control for brain activation caused by actual muscle contractions, muscle activity was recorded using surface sensors to collect raw EMG signals during the MIQ-3 arm movement protocol for each condition (e.g., physical, KI, IVI, and EVI) during the fMRI simulation. This ensures that the pattern of brain activity found through fMRI is independent of activity caused by muscle activity. Two EMG sensors with a transmission range of 20 meters (Trigno Wireless EMG System) were placed on the pectoralis major and anterior portion or the deltoideus muscle of the non-dominant hand (left), and adhered to the skin by adhesive interfaces (Delsys, Inc.). These placement locations were chosen because they were the primary movers of the arm rotation task (Figure 2.2). Participants were instructed not to put on any lotions/oils to improve skin/sensor contact. The root mean squared value of the EMG signals (EMGrms) was calculated for each 30 second trial. The mean values for each movement was calculated over three trials of the duration for each condition. Each trial was separated from the next by a rest period (lasting 30 seconds) in order for any muscle activation to cease, and participants to mentally rest.

Procedure

Pre-Screening. After securing Institutional Review Board approval, participation was solicited electronically and by posting calls throughout the university and surrounding campus area. Participation was initiated by visiting a SurveyMonkey website on the solicitation to complete the background questionnaire that screened for conditions unsafe and contraindicative to fMRI scanning (e.g., severe claustrophobia, fracture repaired with metal, history of cancer).

At the initial session, participants with qualifying backgrounds and deemed fMRI safe completed the MIQ-3 and VMIQ-2 which were distributed in a random order to control for order effect. The MIQ-3 scores were used to screen for good imagery ability. The criteria was established through a cluster analysis of the total (n = 206) sample with scores of six or seven for each item classified good imagers. Twenty-eight participants met these criteria. Participants who did not qualify for the fMRI experiment were thanked for their time and did not proceed further in the study. Then, using Microsoft Excel, a random sample of 20 was generated for the fMRI data collection.

fMRI Simulation. To ensure high-quality fMRI data, participants were educated about the fMRI process using a mock fMRI scanner that closely matched the conditions of actual scanning. At this mock session, the meaning of the MIQ-3 conditions were explained, fMRI safety issues were discussed using the fMRI participant screening document from the brain imaging center, and the participant practiced the MIQ-3 protocol in a realistic facsimile fMRI scanner. As part of the protocol, mental chronometric and EMG measurements were collected both outside (standing and physical completing the task) and inside (lying supine imagining the task) the mock fMRI scanner while scanner sound effects were playing. Specifically, participants went through a mock localizer (Siemens_Loacalizer), anatomical scan (Siemens_MPRAGE), and functional scan (Siemens_EPI); all with the sound effects on. The purpose of the fMRI simulation session was for participants to become comfortable with the audible prompts, presentation stimuli, task, and familiar with the scanning procedure. At the conclusion of this session, participants were scheduled for their fMRI scanning session.

Functional Imaging. Within two weeks, the participants attended the scanning session. Functional MRI was performed using a 3T Magneton Trio system (Siemens, Erlanger, Germany) fitted with a 12-channel head coil located at the McCausland Center for Brain Imaging, University of South Carolina at Palmetto Richland Memorial Hospital. Participants were supine on the table with their head immobilized using pillows and foam pads. The MRI scanlasted approximately 45 minutes and included: (1) one 21-second localizer (scout) to localize functional axial slices, (2) one 6-minute and 17 second high-resolution anatomical scan [sagittal T1-weight; repetition time: 2250 ms echo time 4.15 ms; one slab divided into 192 slices; slice thickness: 1 mm; flip angle: 9 degrees; field of view: 256 x 256 mm^2; voxel size: 1 x 1 x 1 mm^3; bandwidth 150 Hz per voxel; echo spacing: 9.4 ms], (3) three 10-minute and 51 second functional runs [ascending, interleaved, transversal; repetition time: 1550 ms; echo time: 34.0 ms; 42 slices; slice thickness: 3.00 mm; flip angle: 71 degrees; field of view: 216 x 216 mm^2; voxel size: 3 x 3 x 3 mm^3; BOLD threshold: 4.00; bandwidth: 1984 Hz per voxel; echo spacing: 0.59 ms], (4) and one 6-minute and 10 second T2-weight resting state scan [descending, interleaved, transversal; repetition time: 1850 ms; echo time: 30 ms; 34 slices; slice thickness: 3.00 mm; flip angle: 75 degrees; field of view: 208 x 208 mm^2; voxel size: 3 x 3 x 3 mm^3; BOLD threshold: 4.00; bandwidth: 2004 Hz per voxel; echo spacing: 0.58 ms]. These scans were administered in the aforementioned order for all participants.

Conditions and Stimuli. The same arm rotation task from the MIQ-3 was used as the imagery stimulus because of its simplicity allowing subjects to control and reproduce the task. This task involved participants slowly extending their non-dominant hand straight out to their side so that it is parallel to the ground, palm down. They then moved their arm forward until it was directly in front of their body (still parallel to the ground). Experimental conditions included KI, IVI, and EVI, as well as a control condition that involved viewing a fixation cross. There were three scanning sessions with six repetitions for each experimental condition, resulting in 18 trials for each experimental condition.

The experimental conditions (i.e., FEELING, INTERNAL Perspective, EXTERNAL Perspective, and REST) were presented in pseudorandomized order (counterbalanced for condition) using Presentation software (NeuroBehavioral Systems, Inc., Berkeley, CA). All stimuli were projected onto a screen positioned behind the fMRI scanner that was seen by the participants through a mirror mounted onto the head coil. Each participant completed three functional scanning runs with a duration of ten minutes and thirty seconds each. Within each run, each participant completed 6 trials in each experimental condition. Each trial lasted twenty-three seconds and consisted of: i) an auditory cue indicating the participant should open their eyes, ii) a visual prompt to inform the participant of the imagery condition (3 seconds) and iii) a blank screen which was presented while the participants engaged in imagery (20 seconds). All participants were instructed to close their eyes after reading the imagery condition and to keep them closed for the duration of subsequent motor imagery. All control (rest) conditions required the participant to stare at a fixation cross in the middle of the screen. Individual trials were separated by a pseudo-randomly chosen temporal jitter of 150, 250, 350 or 450 milliseconds. Following the scanning session, participants completed a post-experiment debriefing questionnaire.

Data Analysis. All data was pre-processed using Statistical Parametric Mapping software (SPM8, Wellcome Trust Centre for Neuroimaging, London). Initially, motion correction in the functional images was completed using SPM realignment. This estimates six rigid-body transformation parameters for each image by finding the parameters that minimize the mean squared difference between it and a reference image. The structural T1-weighted scan was used as the reference image for each subject. This image was co-registered to the mean functional image. The functional and anatomical images were normalized to MNI space using trilinear interpolation method. The scans were smoothed using a Gaussian kernel set at 8 mm full width at half-maximum.

Statistical analyses were completed using a general linear model with separate model regressors for each task condition to describe the data through experimental effects. Six regressors were used (x, y, z, yaw, pitch, and roll). One sample *t*-tests were used to contrast the following experimental conditions: aggregated imagery conditions (KI, IVI, and EVI) minus rest, KI minus rest, IVI minus rest, EVI minus rest, KI minus IVI, KI minus EVI, IVI minus KI, IVI minus EVI, EVI minus IVI, and EVI minus KI. We also calculated the inverse contrasts of IVI minus EVI, KI minus EVI, and KI minus IVI. Comparisons of the functional data were assessed at the $p < 0.001$, uncorrected level. Activated clusters were considered significant if their spatial extent threshold was greater than 3 voxels. The results are presented at the cluster level (k) and peak t-value (local peak activation amplitude), with the associated MNI coordinates (See Figure 2.3 for Chronological Order of Experiment)

Results

Imagery Background

Frequency statistics were computed for the questions on mental imagery background. Approximately 77.8% (n = 14) of the participants indicated that they knew what mental imagery is. From these participants, most defined imagery as imagining or visualizing a task, object or performance in their mind without moving. Additionally, 61.1% (n = 11) indicated that they had previously used mental imagery for performance enhancement specifically in sport, dance or injury rehabilitation.

Mental Chronometry

Participants physically completed an average of 7.44 ± 2.38 (Min = 4.00, Max = 12.67) full arm rotation repetitions in 30 seconds across the three subscales. By scale the averages were: KI = 7.04 ± 2.36, IVI = 7.59 ± 2.76 and EVI = 7.30 ± 2.64. The minimum and maximum scores were: KI: 3.67 and 13.00; IVI: 4.33 and 14.67; and EVI: 4.00 and 13.33.

EMG Activity during fMRI Simulation

When considering raw EMG activity of the pectoralis major muscle and the anterior portion of the deltoideus muscle, separate repeated-measure ANOVAs for each condition was not significant; therefore, the mean value was used for subsequent analyses. In addition, separate EMGrms comparisons between the imagery conditions showed no significant muscle activity for either muscle ($p > 0.05$) (Table 2.1). Accordingly, EMG activity was not used as a regressor in the analysis of fMRI data.

Movement Imagery Questionnaires

The overall mean score for the MIQ-3 was 81.17 ± 2.41 (Range = 76-84) and for each scale: KI = 27.28 ± 0.89 (Min = 25, Max = 28), IVI = 27.17 ± 0.86 (Min = 25, Max = 28), and EVI = 26.72 ± 1.45 (Min = 24, Max = 28). MIQ-3 intra-scale correlations using Spearman's rho for the MIQ-3 ranged between 0.40 and 0.48, indicating scales were related but not multi-collinear ($r > 0.90$).

The overall mean score for the VMIQ-2 was 161.72 ± 15.61, Range = 129-180) and for each scale: 55.00 ± 5.26 for KI, 51.89 ± 8.37 for IVI, and 54.83 ± 5.78 for EVI. The minimal and maximal scores were 44 and 60, 32 and 60, and 41 and 60, KI, IVI, and EVI, respectively. VMIQ-2 intra-scale correlations using Spearman's rho were between 0.41 and 0.70. Inter-scale correlations between the MIQ-3 and VMIQ-2 ranged from 0.54-0.65. See Table 2.2 for descriptive statistics and inter-scale correlations between the MIQ-3 and VMIQ-2.

fMRI Results

Of the 18 participants, 50% of the participants had previously undergone an MRI (n = 9) (e.g., knee, shoulder, ankle), but not necessarily of their brain. The debriefing questionnaire showed that one participant self-reported switching between imagery perspective and modality during the brain-imaging task (with a score less than five). As a result, their data was removed from further analysis. Based on a Likert-scale (1 = not at all to 10 = greatly) the debriefing questionnaire indicated that participants, on average, were able to focus on each imagery perspective (Mean = 7.22 ± 1.26) and each imagery modality (Mean = 7.33 ±1.65) during the scanning session.

Imagery Conditions Compared to Control (Rest) Condition

When all imagery conditions (aggregate of KI, IVI, and EVI) were compared to rest significant activation was found bilaterally in the middle frontal gyrus, frontal rolandic operculum, inferior temporal gyrus, superior and inferior parietal lobule, and precentral gyrus. Additionally, significant activation was found in the frontal cortex (i.e., left superior frontal gyrus, middle frontal orbicularis, and inferior frontal triangularis), temporal cortex (i.e., left temporal rolandic operculum and superior temporal pole), and various subcortical areas (i.e., right cerebellum (Lobule VI and Crus I), and left insula and hippocampus). Lastly, the right inferior occipital gyrus was the only visual area activated when all imagery conditions were compared to rest (Table 2.3).

Examination of individual comparisons confirmed a number of our predictions. KI elicited activations in the inferior parietal lobule (bilaterally), frontal areas (i.e., bilateral inferior frontal orbicularis, left middle frontal gyrus, and right inferior frontal opercularis), left putamen, and right cerebellum (Crus I). There were also activations bilaterally in the middle and inferior temporal gyri and calcarine, left thalamus and SMA, and right insula and postcentral gyrus (Table 2.3).

IVI elicited activations similar to KI, but also recruited sites in the bilateral inferior frontal orbicularis and middle temporal gyrus, right inferior frontal opercularis, superior temporal gyrus, postcentral gyrus, insula and cerebellum (Lobule VI), and the left inferior temporal gyrus, inferior parietal lobule, SMA, inferior frontal triangularis, middle frontal orbicularis, superior temporal gyrus, temporal rolandic operculum, superior temporal pole and insula. Expected activations were also found in the superior parietal areas (i.e., bilateral superior parietal lobule and left precenetral gyrus) (Table 2.4).

As predicted, EVI recruited sites in the occipital cortex (i.e., right inferior occipital gyrus and let middle occipital gyrus), superior parietal areas (i.e., bilateral precentral gyrus, left SMA, right superior parietal gyrus, and right postcentral gyrus), and the inferior parietal lobe bilaterally. Significant activations were also found bilaterally in the inferior frontal orbicularis, middle frontal gyrus, middle temporal gyrus, the left inferior frontal triangularis, middle frontal orbicularis and putamen, and the right inferior frontal opercularis, superior temporal gyrus, superior temporal pole, supramarginal gyrus, cerebellum (Lobule VI) and insula (Table 2.4).

Contrasts across Imagery Conditions

When IVI was subtracted from KI, motor-related areas with significant activations were found in the left superior frontal gyrus, inferior parietal lobule, SMA and hippocampus, and the right caudate nucleus and cerebellum (Lobule VIIb and Lobule VIII). Although the contrast of EVI subtracted from KI showed less activations, there were still significant activations in the right SMA and thalamus as well as the vermis (III). Neither contrast showed peak activations in occipital areas, consistent with KI activating more motor-related areas (Table 2.5).

When KI was subtracted from IVI, no significant activations were present. In addition, when EVI was subtracted from IVI, the only significantly activated brain area was in the right SMA (Table 2.6).

When IVI was subtracted from EVI, the only area significantly activated relating to the expected ventral visual stream was the left inferior parietal lobule. However, when KI was subtracted from EVI peak activations were found bilaterally in the precentral gyrus. Significant activation sites were also found in the frontal cortex (i.e., right middle frontal gyrus), temporal cortex (i.e., right superior and inferior temporal gyrus, and left middle temporal gyrus), parietal cortex (i.e., right inferior parietal lobule and supramarginal gyrus, and left postcentral gyrus), and the right paracentral lobule (Table 2.7).

Discussion

This was the first study to consider neural network activity differences across imagery abilities while participants purported to be using each of their three MI abilities measured by the MIQ-3, one of the most common instruments used in both behavioral and neural facets of sport sciences. As movement imagery ability continues to be a central mediator, or moderator in at least three prominent theoretical models driving sport science research, instrument validation remains essential for enhancing generalizability of proposed model relationships.

In order to determine common activity across all conditions, the rest condition was subtracted from all of the conditions (KI, IVI, and EVI). There was an overall common neural network comprised of the bilateral inferior frontal orbicularis and middle temporal gyrus, right inferior frontal opercularis, superior temporal gyrus and postcentral gyrus, and the left SMA, which is not consistent with previous research (Jiang et al., in press; Guillot et al., 2008, 2009). Even when all imagery conditions (KI, IVI, and EVI) were compared to the rest condition our results only suggest similar activation sites that were found previously in the superior and inferior parietal lobules, precentral gyrus, superior frontal gyrus, occipital gyrus, and cerebellum (Lobule VI and Crus I). However, consistent with Jiang et al. (in press), who were the first to examine real-time imagery of a VMIQ-2 movement among those screened by the respective instrument and Guillot et al. (2008, 2009), active networks during KI compared to VI included the superior frontal gyrus, inferior parietal lobule, SMA, cerebellum, and caudate nucleus. In addition, when overall VI was compared to KI there was significant activity in the expected superior parietal areas (i.e., precentral and postcentral gyri, and paracentral lobule) and the inferior parietal lobule, which was all produced by EVI; in contrast, occipital (e.g., primary, secondary and associative visual cortexes) activations were not significant for neither VI ability in our study. These findings may be attributed to the MIQ-3 protocol involving simple, temporally recent motor performance compared to having the participants imagine a past experience with the movement as with VMIQ-2 instructions, or that the participants were only thinking about, not genuinely imagining the movement.

In contrast, considering the difference between rest and activity during each condition separately we subtracted each imagery ability from rest. When rest was subtracted from KI our results were consistent with the previous study by Guillot et al. (2009) showing peak activation in frontal and parietal lobules (specifically the inferior parietal lobule), subcortical areas (i.e., cerebellum and putamen). However, we also received additional activation in the insula associated with motor planning, and the temporal and occipital cortices which have not been found to be associated with KI. When comparing the visual perspectives to the rest condition, similar results were found during both IVI and EVI with significant activations in the precentral gyrus, SMA, and inferior and superior parietal lobules as in previous studies that considered gross motor movements (Jiang et al., in press) or simple motor tasks (Gerardin et al., 2000; Guillot et al., 2008, 2009; Lafleur et al, 2003; Stephan et al., 1995). IVI and EVI also activated areas associated with working memory and memory retrieval (i.e., inferior and middle frontal gyri) (Leung, Gore, & Goldman-Rakic, 2002; Pochon et al., 2002; Rama et al., 2001; Ranganath, Johnson, & D'Esposito, 2003, Sun et al., 2005; Zhang, Leung, & Johnson, 2003), motor planning (i.e., insula and supramarginal gyrus) (Beurze, de Lange, Toni, & Medendorp, 2007; Meister et al., 2007), visual mental imagery (i.e., inferior and middle occipital gyri) (Platel et al., 1997), and voluntary hand movement (i.e., postcentral gyrus) (Bernard, et al., 2002). These data provide evidence that these areas are likely to be involved with updating information in working memory to accurately plan for the motor movement and the actual visual mental imagery of the MIQ-3 arm rotation task.

The visual imagery perspectives (IVI and EVI) were also compared to the rest condition. For IVI, peak activation found in the precentral gyrus, SMA, and inferior and superior parietal lobules are consistent with recent studies by Guillot et al. (2008) and Jiang et al. (in press). Our results also showed peak activations in the inferior frontal areas, middle and superior temporal gyri and subcortical areas, possibly reflecting participants using brain areas for motor planning (Beurze, de Lange, Toni, & Medendorp, 2007) and motor preparation (Alexander & Crutcher, 1990); however, increased activity in the temporal cortex has not been found to be related to either IVI or EVI. Furthermore, compared to IVI, EVI revealed an increased amount of activity in the middle and inferior occipital gyri. Increased occipital activation during EVI when compared to the rest condition is likely due to the role of EVI in visuospatial processing involving a visual representation of the action (Mahoney & Avener, 1977), which has been considered a truer form of VI (Hall, Rodgers, & Barr, 1990; Janssen & Sheikh, 1994; White & Hardy, 1995).

In order to isolate dominant neural areas discriminating each imagery ability, all possible differences between conditions were examined. When comparing KI with the VI perspectives, results indicated more activation in subcortical brain areas when EVI was subtracted from KI, but activations were in the SMA, vermis (III) and thalamus, not the caudate nucleus, inferior frontal triangularis, or inferior frontal orbicularis as Jiang et al. (in press) found. However, more activity in the caudate nucleus was found when IVI was subtracted from KI, as well as peak activity in the superior frontal gyrus, inferior parietal lobule, hippocampus, and cerebellum (Lobule VIIb and Lobule VIII), while Jiang et al. (in press) found no peak activations for this contrast. The significant activation of the superior frontal gyrus when IVI, but not EVI, were subtracted from KI may be related to the functional involvement of this network in self-awareness and in coordination with the action of the sensory system (Goldberg, Harel, & Malach, 2006). Although results for KI compared to the VI perspectives showed increased activity in different areas compared to recent research (e.g., Jiang et al., in press), these data are consistent with studies identifying that subcortical brain areas are related to action control (Graybiel, 2000; Schubert, von Cramon, Niendorf, Pollmann, & Bublak, 1998), which correspond with the timing, force and exactness of reference properties of KI (Denis, 1985).

While IVI minus KI and EVI minus KI showed a large overlap in activity in previous studies (i.e., inferior parietal lobule, middle temporal gyrus, middle occipital gyrus, and angular gyrus), the present study’s activations were not evident when KI was subtracted from IVI. However, the contrast between EVI and KI showed similar peak activations like Jiang et al. (in press) in the inferior parietal lobule, and the superior and middle temporal gyri. Compared to results found by Jiang et al. (in press), divergent brain activity patterns were observed in the inferior temporal gyrus, precentral and postcentral gyri, supramarginal gyrus, and paracentral lobule when KI was subtracted from EVI. Although current results are inconsistent with imagery ability studies, these brain areas are associated with planning and executing voluntary movements (Bernard et al., 2002; Meister et al., 2004) and motor imagery (Munert, Zentgraf, Stark, & Vaitl, 2008; Porro et al., 1996; Sharma, Jones, Carpenter, & Baron, 2008; Tomasino, Werner, Weiss, & Fink, 2007) which are needed to complete the arm rotation task used in the present study. Furthermore, it is important to note that neither visual imagery perspective was significantly activated when compared to KI as expected relative to previous studies (e.g., Jackson et al., 2006; Solodkin et al., 2004; Thompson & Kosslyn, 2000), suggesting that participants were using the same occipital areas of the brain during KI as those used for VI and not exclusively imagining how the movement feels.

Directly comparing the two visual imagery perspectives only showed significant peak activation in the inferior parietal lobule when IVI was subtracted from EVI. Although Jiang et al. (in press) also found significant activation in the inferior parietal lobule when subtracting IVI from EVI, they also found activity in the superior and middle temporal gyri, middle occipital gyrus, and angular gyrus. Moreover, our results are inconsistent with Jiang et al. (in press) who did not find peak activation in the SMA when EVI was subtracted from IVI, but found increased activation in a large number of brain areas related to voluntary hand movement, working memory, memory retrieval, and motor and visual mental imagery (e.g., middle and superior frontal gyri, precentral gyrus, inferior and superior parietal lobules, middle and superior occipital gyri, and several subcortical areas). Because peak activations were not found when directly contrasting the two visual imagery perspectives (IVI minus EVI), similar brain areas are suggested to be used during MI of an upper extremity arm rotation task. This is inconsistent with previous findings by Jiang et al. (in press) and our hypotheses for the increased activation of specific visual streams for IVI (dorsal visual stream) and EVI (ventral dorsal stream).

This evidence of biological inconsistency corroborates inconsistencies found in behavioral imagery perspective studies showing different effect on motor learning and performance depending on the perspective used during imagery training programs. For example, Callow et al. (2013) demonstrated that IVI was more effective than EVI for a task focused on the planning of movements in response to changes in the visual field, while Hardy and Callow (1999) found that EVI was more effective than IVI for tasks dependent on the visuospatial processing of a movement. Studies in the behavioral and neuroscience literature have provided additional evidence for neurological distinctions between imagery perspectives (e.g., Callow et al., 2013; Callow & Hardy, 2004; Fourkas, Avenanti, Urgesi, & Aglioti, 2006; Jiang et al., in press; Ruby & Decety, 2003). However, our results do not provide additional evidence that distinguishes between imagery perspectives based on underlying brain areas. Instead, we found that IVI and EVI appear to activate similar brain areas, and distinctions (activating more brain areas) were only found when KI was subtracted from EVI. A possible explanation for these imagery perspective brain area inconsistencies could be the task type, temporal recency with the movement experience and imagery instructions. Unlike the VMIQ-2, the MIQ-3 tasks are simple movements, experienced right before the imagery component and the instructions specify rating the ease of using imagery abilities rather than the degree of vividness. Additionally, the arm rotation task should have activated different brain areas than a t task involving a whole body movement such as the stair climbing action used in the Jiang et al. (in press) study. Therefore, subsequent studies are needed comparing neural activity areas for within questionnaire movements that differ in motor properties (e.g., the MIQ-3 arm rotation and whole body jump movement).

It is also important to point out that our results are inconsistent with previous studies (e.g., Guillot et al., 2008, 2009; Jiang et al., in press, Solodkin et al., 2004) in that there was a significant amount of temporal cortex activation for all imagery ability conditions when compared to rest, and specifically when KI was subtracted from EVI. This is unusual because the temporal cortex is usually found to be associated with the observation of motion (Rizzolatti et al., 1996) and visual motion processing (Beer, Blakemore, Previc, & Liotti, 2002; Deutschlander et al., 2002; Dupont, Orban, de Bruyn, Verbruggen, & Mortelmans, 1994), which are both associated with movement preparation or interpreting the meaning of visual stimuli and not necessary with MI. However, this increased activation may have been caused by participants using memory recall and retrieval strategies to imagine the arm rotation movement as the temporal cortex links conscious memory processes and the ventral visual pathway (Danckert, Gati, Menon, & Kohler, 2007; Douglas, Phelps, & Davachi, 2007). Given the temporal recency of the written MIQ-R instructions, this activity could also reflect the processing of the spatial location of the instruction screen relative to the participant.

Compared to studies in the behavioral sport science literature, especially those examining imagery training programs, advocating for the use of either IVI or EVI depending on the type of task in question, our results do not support previous research (Goodale, 2011; Milner and Goodale, 2008) distinguishing between visual streams for specific VI abilities. From the data presented here, we suggest that EVI and IVI may actually involve more common neural processes than independent processes. Moreover, previous research suggests (de Haan & Cowey, 2011) that there may be more than two pathways because neurophysiological evidence does not clearly support present pathway models or pathway models used in VI.

Regarding brain activity patterns between VI (IVI and EVI) and KI, we found similar overlapping brain activation to Guillot et al. (2009) including motor-related areas, frontal areas, and the inferior parietal lobule. When comparing VI ability perspectives separately, there was a lack of increased activity for IVI in occipital areas and superior parietal areas when compared directly to KI. By contrast, a divergent pattern of increased activity was observed when EVI and KI were compared directly; EVI activated predominantly temporal areas and the precentral and postcentral gyri, whereas KI only yielded more activity in the inferior parietal lobule. These results advance Guillot et al.'s (2008) study suggesting that IVI and KI may use similar neural systems, while EVI and KI are mediated through separate neural systems which may have implications for what type of imagery is used in neurorehabilitation and motor learning.

This study is unique because it was only the second study to examine the brain networks used for different imagery perspectives and modalities. Unlike previous fMRI work, we restricted our sample to female participants because other studies have shown higher self-report MIQ scale scores among this population (e.g., Campos & Perez, 1988; Campos & Sueiro, 1993; Goss et al., 1986; Isaac & Marks, 1994). As recommended by Guillot and colleagues (2009) to account for possible confounding neural activity across the three imagery conditions, we considered EMG data in the pectoralis major and deltoideus muscles but found no differences, precluding the need to statistically control for this activity. We also verified that participants' imagery speed was consistent across conditions and with the pace of physically performing the movement with mental chronometry finding no significant differences.

Four limitations of the current study should be considered in future investigations. First, our sample was restricted to females classified as having good imagery abilities calling for a male sample replication. BOLD response comparisons between those who score low and high imagery ability scale is also warranted. The second limitation relates to the type of movement used for the imagery task that may introduce some variations in the underlying brain activation and BOLD signal due to possible differences between upper extremity and lower extremity movements as well as gross and fine motor movements. This only presents a potential confounding factor between studies that may cause a difference in significantly activated brain areas, but may have a significant impact on using imagery for motor-rehabilitation of the upper extremity compared to lower extremity. Therefore, subsequent studies should examine a lower extremity movement of the MIQ-3 in a similar manner (i.e., knee lift). Third, the present study considered neural activity relating only to three specific imagery abilities related to movement and did not tap any abilities used to create cognitive and affective image content as measured by Williams and Cummings' (2011) Sport Imagery Ability Questionnaire. Lastly, the gross motor MIQ tasks preclude confirmation of common neural substrates during MI and physical performance of the movements because MIQ-3 movements are not possible in current fMRI machines.

Despite some inconsistencies with Jiang et al. (in press), the present findings provide initial biological validation of the MIQ-3 subscales. Specifically, distinct brain activity for imagery perspectives and modalities was demonstrated reflecting those that mediate the specific types of imagery abilities delineated in the MIQ-3. This scale-specific neural activity is evidence of VMIQ-2 convergent validity because the participants screened as having good imagery abilities with the MIQ-3 also scored respectively better on the VMIQ-2 scales. Additionally, the moderate inter-scale correlations on the full 206 participants are more direct evidence of construct validity. Furthermore, the present findings contribute to theoretical and practical implications in the sport science literature for motor learning and rehabilitation. First, based on research demonstrating imagery benefits for enhancing motor performance and facilitating motor learning (e.g., Guillot et al., 2008) across a variety of tasks, it is necessary to understand the underlying neural processes for each type of imagery ability. Although our results are inconsistent with previous literature (Guillot et al., 2009; Jiang et al., in press), we propose that additional studies reexamine the brain activity associated with each imagery ability so that we can be confident in assigning a specific type of imagery during neural rehabilitation to encourage cerebral plasticity following imagery-based training programs (Lacourse, Turner, Randolph-Orr, Schandler, & Cohen, 2004). Second, in lieu of the revised applied model of deliberate imagery use for sport, dance, exercise, and rehabilitation, further biological evidence delineating the breadth of imagery abilities encompassed by the model is warranted. These findings will help researchers and practitioners establish better imagery intervention to further enhance behavioral and cognitive performance in motor-related domains.

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Table 2.1

Descriptive Statistics of the Raw EMGrms Data

	M	SD	*F*	*p-value*
Pectoralis Major				
Physical	244.59	501.49	2.1	0.14
KI	17.59	36.75	1.08	0.35
IVI	16.66	31.59	1.45	0.25
EVI	16.59	29.03	0.65	0.53
Deltoidius (anterior portion)				
Physical	236.06	274.69	1.38	0.26
KI	20.11	2.48	0.73	0.49
IVI	20.04	2.34	0.97	0.39
EVI	19.95	2.21	0.65	0.53

*Note.** $p < 0.05$

Table 2.2

Descriptive Statistics and Inter-Scale Correlations between the MIQ-3 and the VMIQ-2

	KI		IVI		EVI	
	M	SD	M	SD	M	SD
MIQ-3	27.28	0.89	27.17	0.86	26.72	1.45
VMIQ-2	55.00	5.26	51.89	8.37	54.83	5.78
R	0.65		0.54		0.60	

Note. *r* = MIQ-3 and VMIQ-2 inter-scale correlations; α and r: n = 206

Table 2.3

Brain Areas Significantly Activated during All Imagery Conditions and KI Compared to Rest

		All – Rest					KI – Rest				
Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[d]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]
		X	Y	Z	K		x	y	z	k	
Frontal Cortex											
Frontal Sup	L	-24	-8	52	7365	8.73					
		-18	68	10	4	4.00					
Frontal Inf Orb	L	-40	44	-16	28	5.36	-40	44	-16	26	5.77
		-50	38	-6	44	3.75	-46	44	-2	56	4.31
	R	50	38	-10	384	4.65	52	28	-2	36	4.04
							50	38	-10	15	4.03
Frontal Mid Orb	L	-40	54	-12	28	4.00					
		-46	46	-2	44	4.41					
		-26	52	-12	4	3.94					
Frontal Mid	L	-42	38	30	205	5.17	-36	38	26	202	5.36
		-46	30	32	205	4.97	-38	28	32	202	4.38
	R	42	48	24	3	3.89					
Frontal Inf Tri	L	-38	28	30	205	4.64					
Frontal Inf Oper	R	58	12	12	384	4.58	58	12	14	26	4.12
Rolandic Oper	L	-50	6	14	860	6.53					
		-48	4	2	860	5.80					
	R	60	8	30	8	4.16					
		60	4	12	26	3.84					
Temporal Cortex											
Temporal Mid	R	44	-42	8	294	8.23	46	-44	8	92	5.43
		62	-44	12	294	4.49	56	-70	6	3	3.96
		56	-70	6	82	4.29					
	L	-52	-54	12	3731	7.09	-50	-30	-12	216	6.37
Rolandic Oper	L	-48	6	16	1369	6.81					
Temporal Pole Sup	L	-48	10	0	1369	5.93					

Temporal Inf	R	58	-64	-2	82	4.53	50	-18	-22	9	4.00
		50	-20	-18	28	4.18					
	L						-54	-26	-18	216	4.82
							-46	-16	-26	216	4.55
							-44	-4	-26	9	3.86
Temporal Sup	R	68	-30	10	23	4.08	68	-30	22	3	3.87
		68	-32	18	23	4.01					
Parietal Cortex											
Parietal Sup	L	-24	-66	62	3731	7.99					
	R	28	-46	60	810	4.79					
		16	-66	58	184	5.97					
Parietal Inf	L	-40	-42	56	3731	7.66	-44	-40	48	2272	5.92
	R	36	-46	48	810	6.17	36	-44	46	235	4.35
Postcentral	R	30	-32	56	230	4.57	28	-46	58	235	4.06
Motor/Premotor Cortex											
Supp Motor Area	L	-6	-4	64	7365	12.20	-6	-4	66	5721	11.32
		-6	-8	72	7365	11.81					
Precentral	L	-58	-4	32	1369	5.15					
	R	60	10	30	384	4.78					
Occipital Cortex											
Occipital Inf	R	48	-76	-10	82	4.26					
Calcarine	L						-24	-68	62	2272	7.85
	R						16	-66	64	72	4.76
Subcortical Areas											
Cerebellum (VI)	R	38	-60	-24	230	6.69					
Cerebellum (Crus I)	R	36	-78	-22	7	4.37	36	-78	-22	17	4.68
Insula	L	-30	18	8	36	4.12					
	R						48	14	-2	36	3.95
Hippocampus	L	-22	-14	-20	5	3.91					
Putamen	L						-30	-10	52	5721	9.63
Thalamus	L						-14	-12	64	5721	9.18

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p <$ 0.001 level.

Table 2.4

Brain Areas Significantly Activated during IVI and EVI Conditions Compared to Rest

		IVI – Rest					EVI – Rest				
Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]
		X	Y	Z	K		x	y	Z	k	
Frontal Cortex											
Frontal Inf Orb	R	50	38	-10	65	4.62	48	38	-12	104	4.79
	L	-40	44	-16	19	4.19	-40	42	-16	22	5.04
		-42	44	-2	5	3.80					
Frontal Inf Tri	L	-40	38	28	93	4.38	-38	28	28	149	4.79
		-46	30	30	93	4.32					
Frontal Inf Oper	R	58	14	12	40	4.31	58	12	14	336	4.68
		58	14	30	13	4.24	48	14	0	278	4.08
Frontal Mid Orb	L	-36	56	-12	19	4.20	-40	44	-2	33	4.45
Frontal Mid	L						-44	36	32	149	4.96
	R						44	48	22	7	3.94
Temporal Cortex											
Temporal Mid	L	-52	-58	12	2570	6.96	-52	-56	14	3450	7.23
		-50	-30	-12	259	5.82	-60	-20	0	77	4.73
		-60	-22	2	10	4.00					
	R	46	-44	8	196	6.51	56	-70	6	217	4.31
		62	-44	12	23	4.57					
Temporal Sup	L	-56	-44	20	2570	6.65					
	R	68	-30	14	16	4.31	38	-34	14	372	4.80
							60	-44	14	372	4.65
Rolandic Oper	L	-48	6	16	1142	6.88					
Temporal Pole Sup	L	-50	10	-4	1142	5.99					
	R						44	14	-20	278	5.02
Temporal Inf	L	-60	-62	-6	13	4.35					
Parietal Cortex											

Parietal Sup	L	-24	-66	64	2570	8.17					
	R	18	-66	56	94	4.88	16	-64	56	244	7.74
							30	-50	64	992	5.00
Postcentral	R	64	-6	28	24	4.34	62	-6	32	336	4.83
Parietal Inf	L	-58	-30	44	10	3.90	-36	-44	52	3450	8.53
							-44	-40	48	3450	8.10
	R						36	-44	46	992	6.83
							38	-36	48	992	6.61
Supramarginal	R						56	-28	48	23	4.44
Motor/Premotor Cortex											
Supp Motor Area	L	-2	2	60	6667	10.93	-2	-6	66	9366	13.60
		-6	-4	64	6667	10.17	-2	0	58	9366	12.74
		-6	-6	72	6667	10.03					
Precentral	L	-58	-4	30	1142	4.89	-32	-10	54	9366	8.97
	R						60	4	24	336	5.84
Occipital Cortex											
Occipital Inf	R						48	-80	-4	217	4.53
Occipital Mid	L						-46	-76	2	36	4.24
Subcortical Areas											
Cerebellum (VI)	R	38	-60	-24	192	6.42	38	-58	-24	234	7.97
Insula	L	-30	18	8	31	4.14					
	R	46	14	-20	15	3.91	48	6	-18	278	4.35
		48	14	-2	4	3.80					
Putamen	L						-32	-12	16	28	5.61

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Table 2.5

Brain Areas Significantly Activated during KI Compared to EVI and IVI.

Area	L[a]/R[b]	KI - EVI					KI - IVI				
		Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]
		X	Y	Z	k		x	y	Z	k	
Frontal Cortex											
Frontal Sup	L						-24	46	42	11	4.13
Parietal Cortex											
Parietal Inf	L						-52	44	56	5	3.97
Motor/Premotor Cortex											
Supp Motor Area	R	12	-4	70	16	4.18					
		4	8	70	7	3.88					
	L						-10	22	66	15	4.28
Subcortical Areas											
Vermis (III)		0	-34	-48	36	3.91					
Thalamus	R	18	-14	8	16	4.15					
Caudate	R						14	8	22	40	4.48
Hippocampus	L						-22	-26	-6	6	4.01
Cerebellum (VIIb)	R						28	-74	-46	6	3.93
Cerebellum (VIII)	R						18	-68	-40	8	3.94

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Table 2.6

Brain Areas Significantly Activated during IVI Compared to EVI and KI.

		IVI-EVI					IVI-KI				
Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]
		X	Y	Z	k		x	y	Z	k	
Motor/Premotor Cortex											
Supp Motor Area	R	14	-6	68	4	3.79					

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Table 2.7

Brain Areas Significantly Activated during EVI Compared to IVI and KI.

		EVI-IVI					EVI-KI				
Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]
		X	Y	Z	k		x	y	Z	k	
Frontal Cortex											
Frontal Mid	R						40	32	24	7	3.98
Temporal Cortex											
Temporal Sup	R						46	-24	60	497	4.68
Temporal Inf	R						54	-62	-4	23	4.21
Temporal Mid	L						-46	-62	16	66	4.13
							-46	-70	20	66	3.94
Parietal Cortex											
Parietal Inf	L	-38	-46	46	7	3.92					
	R						48	-38	54	497	5.74
Postcentral	L						-48	-14	46	213	4.77
							-48	-8	58	213	4.53
Supramarginal	R						36	-38	42	497	6.59
Motor/Premotor Cortex											
Precentral	L						-40	-8	56	213	4.23
							-22	-14	64	50	4.46
							-30	-18	58	50	3.76
	R						46	8	32	43	4.10
							52	12	36	43	3.92
Paracentral Lobule	R						0	-30	68	3	3.82

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Figure 2.1
MIQ-3 arm rotation task

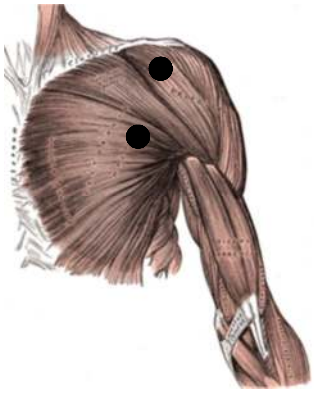

Figure 2.2
Electromyography surface sensor placement

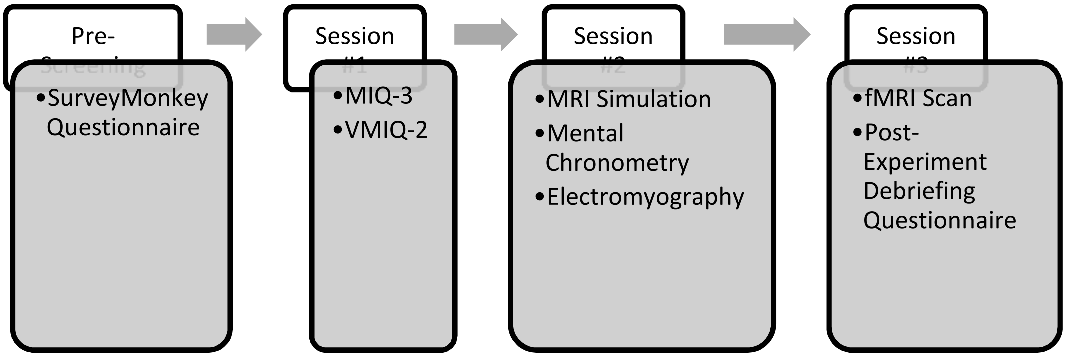

Figure 2.3
Chronological order of experiment

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CHAPTER 3: JOURNAL ARTICLE 2

BIOLOGICAL EVIDENCE FOR INTER-INDIVIDUAL DIFFERENCES IN MOVEMENT IMAGERY ABILITIES[2]

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[2] Seiler, B. D., Monsma, E., & Newman-Norlund, R. To be submitted to *Journal of Sport and Exercise Psychology.*

Imagery is a top-down, knowledge driven process involving the generation or regeneration of parts of a brain representation or neural network (i.e., when more than one area/region is consistently activated) that is under the conscious control of the individual (Holmes & Calmels, 2008). Specifically, motor imagery (MI) is a dynamic state that enables an individual to mentally stimulate their mind to rehearse an action without engaging in overt physical movements (Moran et al., 2012; Olsson & Nyberg, 2010), and is subdivided into different modalities including visual and kinesthetic imagery. Visual imagery (VI) requires imagining from an internal or external perspective, while kinesthetic imagery (KI) requires one to feel the movement. There is now evidence showing that MI and movement execution share similar neural networks (Cuthbert, Vrana, & Bradley, 1991; Gerardin et al., 2000; Szameitat, Shen, & Sterr, 2007), and that imagined movements retain the same temporal characteristics as the corresponding overt movement (Decety & Jeannerod, 1996; Decety et al., 1989; Jeannerod, 2001). Although not fully overlapping, this relationship between MI and movement execution can be used to explain behavioral research showing matched perceptual performances of executed versus imagined stimuli.

Results from previous studies have shown that MI can improve the performance and learning of a variety of motor tasks (Feltz & Landers, 1983; Guillot & Collet, 2008) dependent on an individual's level of expertise. For example, through fMRI Wei and Luo (2010) provided additional evidence for an inverse relationship between brain activity and skill level (see Lotze et al., 2003; Ross et al., 2003) by showing that sport experts have a focused cerebral activity pattern found in experience-related motor tasks compared to novices. This economy of effort or neural efficiency in the brain of experts, although at an increased level, may account for their enhanced motor performance.

Motor learning and performance outcomes (Munroe et al., 2000; Murphy, 1994) and imagery intervention effectiveness (Hall, Buckolz, & Fishburne, 1992) are dependent on other individual-dependent variables like imagery ability (Guillot & Collet, 2005; Martin, Moritz, & Hall, 1999; Cumming et al., 2013). Findings in neuroscience note that imagery ability is one of the most variable factors altering neural activity (Guillot et al., 2008), and aligned with Paivio's (1985) notion that imagery ability is a product of genetics interacting with experience, several psychological, behavioral and neuroscience studies support the inter-individual capacity to elicit mental images. Based on MIQ scores, Robin et al. (2007) have demonstrated this showing that good imagers performed significantly better than poor imagers on tennis performance. Similar findings were found when examining the relationship between imagery ability and the acquisition, retention and reacquisition of movements (Goss, Hall, Buckolz, & Fishburne, 1986) as well as how it affects learning in gymnastics (Lawrence, Callow & Roberts, 2013). These studies indicate that good imagery ability is associated with MI practice of motor performance, especially facilitating the acquisition of a movement.

Previous neuroscience research has distinguished brain areas that are active during imagery compared to rest (Binkofski et al., 2000; Guillot et al., 2008, 2009; Jiang et al., in press; Seiler et al., in review; Solodkin et al., 2004), as well as the brain areas that are active during imagery and the physical execution of a task (Guillot et al., 2008, 2009; Solodkin et al., 2004) indicating similar behavioral and anatomical characteristics of movement execution. It is also increasingly evident through fMRI studies that regional brain activity distinguishes the three movement imagery abilities (KI, IVI, and EVI). Most recently, Jiang et al. (in press) used the VMIQ-2 to screen good imagery ability participants and compared regional activity during imagery of the stair climbing item while using each of the three abilities. Results indicated activity in the SMA during each type of imagery, while also showing divergent patterns for KI (i.e., subcortical areas), IVI (i.e., parietal lobule), and EVI (i.e., temporal cortex). While this study laid the foundation for fMRI cross validation of movement imagery ability assessments and BOLD responses during real time imagery there are some notable limitations. First, the VMIQ-2 movements involve recall of past experiences which could be highly variable across participants regardless of their imagery ability, confounding the intensity and perhaps regional breadth of neural activity. Guillot et al. (2009) also recommended that "electromyography (EMG) data should be used to record the muscular quiescence during MI and to ensure that the pattern of cerebral activations observed during MI was not due to any movement" (p. 2166).

To address these limitations, Seiler et al. (in review) used the MIQ-3 to screen for good imagery ability participants in their cross validation with fMRI BOLD response during real-time imagery of the MIQ-3 arm rotation movement. The MIQ-3 protocol involves physically completing a movement prior to using a specified imagery ability to imagine that movement, thus, minimizing the movement experience variability weakness of the VMIQ-2. Moreover, movement-related EMG activity and temporal equivalence between physically performing each movement and imagery of those using each of the abilities were verified as being consistent across conditions through mental chronometry (i.e., physically performing the movement, KI, IVI and EVI). Results were similar to the work of Guillot et al. (2008) and to some extent with (Jiang et al., in press) when comparing imagery to a rest condition in that the inferior frontal orbicularis, inferior and superior parietal lobules, SMA, precentral gyrus, and cerebellum were consistently activated during IVI. However, unlike Jiang et al. (In press), there were less peak activities during IVI contrasted with KI and EVI. There was additional activity in the parietal (i.e., postcentral and supramarginal gyri) and motor/premotor (i.e., precentral gyrus and paracentral lobule) cortices when KI was subtracted from EVI and peak activations in the superior frontal gyrus, inferior parietal lobule, SMA, and subcortical areas when KI was contrasted with IVI, which were inconsistent to those observed in Jiang et al.'s (in press) study.

The results of the latter two studies (Jiang et al., in press; Seiler et al., in review) indicate that the neural networks underlying each imagery ability (KI, IVI, and EVI) remain inconclusive, and may reflect the studies' features such as the variability in questionnaire protocol, the movement task characteristic or the participant characteristics. In order to elucidate inter-individual differences in neural activity aligned with the recommendations of Jiang et al. (in press) the present study extended the results of Seiler et al. (in review) by comparing the good imagers from that study to a separate sample of poor imagers as screened by the MIQ-3. Until now, only Guillot et al. (2008) have considered neural activity comparisons between good and poor imagers using an earlier version of the MIQ-R (Martin et al., 1997), but during both imagery and physical performance of a sequential finger task. Although restricted only to the IVI condition, the good imagery group reported more activation in the parietal and premotor areas when compared to poor imagers, while the poor imagers displayed a wider distributed network activity including the cerebellum, frontal and cingulate cortices. Furthermore, their participants were subjected to a battery of tests (i.e., global imagery score) to screen good and poor imager groups clouding the biological validity of the MIQ movements.

Therefore, the purpose of this study was twofold. First, we examined the convergent validity between like scales (KI, IVI, and EVI) for the MIQ-3 and VMIQ-2 by examining mean differences between good and poor imagery ability participant groups. Second, to cross-validate self-reported and neural measures of imagery ability, we compared fMRI-BOLD signals of participants screened as having good to those screened as having poor imagery abilities with the MIQ-3 during real-time imagery of the arm rotation movement. Aligned with Guillot et al. (2008), we expected that even though both groups may show similar activations, the poor imager group would activate a more diffuse brain network compared to the good imager group who would show greater intensity in fewer areas. More specifically, based on previous findings (Binkofski et al., 2000; Guillot et al., 2008, 2009; Jiang et al., in press) it was hypothesized that compared to participants with good imagery abilities, motor-related areas (i.e., premotor cortex and SMA, frontal areas (i.e., prefrontal cortex, cingulate cortex, and inferior frontal areas) and subcortical areas were expected to have lower peak activations in the poor imagery group for KI. In addition, lower peak activations would be observed in motor-related areas, the superior and inferior parietal lobules, and the dorsal visual stream during IVI of poor imagers compared to good imagers. Instead, greater activity was expected in motor-related areas and the inferior and superior parietal lobules among good imagers. Furthermore, unlike IVI, we expected higher peak activations in the ventral visual stream for EVI in participants screened as having good imagery abilities compared to those with poor imagery.

Method

Participants

From an initial screening of 206 participants, 37 healthy, right-handed female participants between 18 and 30 years old (Mean age = 23.43 ± 2.69) who were screened as having good or poor MIQ-3 scores were selected and placed into good or poor imagery ability groups. All participants were screened as right handed (Edinburgh Handedness Inventory (EHI) Mean = 91.75 ± 12.41), had normal or corrected-to-normal vision, self-reported no history of neurological of psychiatric disorders and were not taking any neurological altering medications.

The good imagery group was composed of 18 participants between 20 and 30 years of age (Mean = 23.72 ± 2.42) and screened as right-handed (EHI Mean = 94.16 ± 9.26). Participants were 15 non-Hispanic White Americans, one Black/African American, one Hispanic/Hispanic American, and one Asian/Asian American. The highest education level included high school diploma (n = 5), bachelor degree (n = 10), and master’s degree (n = 3). Good imagers’ sport history varied (e., basketball, soccer, gymnastics, lacrosse, and rugby), while two participants did not report any sport history.

Nineteen participants comprised the poor imagery group and were 19 to 28 years of age (Mean = 23.16 ± 2.97) and screened as right-handed (EHI Mean = 89.46 ± 14.68). In this group, participants were 18 non-Hispanic White Americans and one Hispanic/Hispanic American. The highest education level was a high school diploma (n = 7), bachelor degree (n = 7), and master's degree (n = 5). The sport history of poor imagers varied (e.g., dance/ballet, golf, equestrian, fencing, and soccer), while four participants did not report any sport history.

Imagery Assessments

Movement Imagery Questionnaire-3 (MIQ-3: Williams et al., 2011). The MIQ-3 is comprised of 12 items measuring the self-reported ease or difficulty of generating images of four separate movements (arm rotation, jump, knee lift and toe touch) each along three subscales: KI, IVI and EVI. After physically performing each movement and imagining oneself performing the movement, participants rate the difficulty of imaging each movement using a 7-point Likert-scale from 1 (very hard to see/feel) to 7 (very easy to see/feel). Subscale scores for the MIQ-3 range from 4-28 where better scores represent better imagery ability. The MIQ-3 displays adequate internal consistency ($\alpha > 0.69$) and concurrent validity with the VMIQ-2 (Williams et al., 2011), and in the present study KI = 0.87, IVI = 0.83, and EVI = 0.88 with moderate inter-scale correlations (KI versus EVI: $r = 0.35$; KI versus IVI: $r = 0.51$ and EVI versus IVI: $r = 0.57$, $p < 0.01$).

Vividness of Movement Imagery Questionnaire-2 (VMIQ-2: Roberts et al., 2008). The VMIQ-2 assesses self-reported imagery vividness (i.e., clarity and realism) and is comprised of 12 motor tasks for each of the three subscales: KI, EVI, and IVI. Participants recorded a score based on the clarity associated with representing each movement mentally using a 5-point Likert-scale from 1 (perfectly clear and vivid) to 5 (no image at all, you only know that you are “thinking” of the skill). In the present study, the VMIQ-2 scale was inversed to be consistent with the MIQ-3 where lower scores represented poor imagery ability and better scores represented good imagery ability. Subscale scores for the VMIQ-2 ranged from 12-60 where better scores represent better imagery ability. Consistent with previous research (Williams et al., 2011, 2012) the internal consistencies of the VMIQ-2 scales in the present study were: KI = 0.95; IVI = 0.94 and EVI = 0.04. Inter-scale correlations were also moderate (KI versus EVI: *r* = 0.39; KI versus IVI: *r* = 0.56 and EVI versus IVI: *r* = 0.65).

Manipulation Check. To assess the extent participants followed the study protocol, participants completed a post-experiment debriefing questionnaire where they were asked to rate the extent they were able to focus on each imagery perspective or modality during the scan, whether they switched between imagery perspectives or imagery modalities, and the extent they were able to focus on the MIQ-3 protocol (i.e., arm movement) on a 10-point Likert-scale (1 = not at all to 10 = greatly).

Mental Chronometry

Consistent with previous work (for review, see Collet et al., 2011; Guillot et al., 2005; Malouin et al., 2008) the temporal congruence between physically executed and imagined actions was evaluated by asking the participants to physically perform and imagine the arm rotation task (Figure 3.1) using each of the MIQ-3 abilities repeatedly for 30 seconds at a personally comfortable cadence. Participants followed audible prompts on a computer screen to begin and end each trial. The number of full MIQ-3 arm movements physically performed over 30 seconds was recorded followed by recording the number of KI, IVI, and EVI repetitions performed while in an fMRI simulation scanner. Physical and imaged repetitions of the MIQ-3 arm movement protocol were averaged across the three trials.

Electromyography (EMG)

Aligned with recommendations (Guillot et al., 2008), muscle activity was recorded using surface sensors to collect raw EMG signals during the MIQ-3 arm rotation movement protocol for each condition (i.e., physical, KI, IVI, and EVI) during the fMRI simulation. Two EMG sensors with a transmission range of 20 meters (Trigno Wireless EMG System) were placed on the pectoralis major and anterior portion or the deltoideus muscle of the non-dominant hand (left), and adhered to the skin by adhesive interfaces (Delsys, Inc.). These placement locations were chosen because they were the primary movers of the arm rotation task (Figure 3.2). Participants were instructed not to put on any lotions/oils to improve skin/sensor connectivity. The root mean squared value of the EMG signals (EMGrms) was calculated for each 30 second trial. The mean values for each movement was calculated over three trials of the duration for each condition. Each trial was separated from the next by a rest period (lasting 30 seconds) in order for any muscle activation to cease, and participants to mentally rest.

Procedure

Pre-Screening. After securing Institutional Review Board approval at the host university, participation was solicited electronically and through posted calls throughout the university and the surrounding campus area. Participation was initiated by visiting a SurveyMonkey website to complete the background questionnaire that screened for conditions unsafe and contraindicative to fMRI scanning (e.g., severe claustrophobia, fracture repaired with metal, history of cancer). At the initial session, participants with qualifying backgrounds and deemed fMRI safe completed the MIQ-3 and VMIQ-2 distributed in a random order to control for order effect.

The imagery ability criterion for the present experiment was devised by completing a cluster analysis to the original raw MIQ-3 data of 206 participants. The analysis indicated four clusters of participant profiles, with a particular cluster of participants that had good imagery ability MIQ-3 scores (e.g., KI > 25, IVI > 25, EVI > 24) and a cluster of participants with poor imagery ability MIQ-3 scores (e.g., KI < 22, IVI < 21, EVI < 23). Participants scoring within the cut-score criteria were selected to participate (good imager group = 28; poor imager group = 25). Then, a computer generated random sample from the qualified participants was selected for the fMRI experiment. Participants who did not qualify for the fMRI experiment based on the cut-scores were contacted to thank them for their time and did not proceed further in the study.

fMRI Simulation. To ensure high-quality fMRI data, participants were educated about the fMRI process using a mock fMRI scanner that closely matched the conditions of actual scanning. At this mock session, the meaning of the MIQ-3 conditions were explained, fMRI safety issues were discussed using the fMRI participant screening document from the brain imaging center, and the participant practiced the MIQ-3 protocol in a realistic facsimile fMRI scanner. As part of the protocol, mental chronometric and EMG measurements were collected both outside (standing and physical completing the task) and inside (lying supine imagining the task) the mock fMRI scanner while scanner sound effects were playing. Specifically, participants went through a mock localizer (Siemens_Loacalizer), anatomical scan (Siemens_MPRAGE), and functional scan (Siemens_EPI); all with the sound effects on. The purpose of the fMRI simulation session was for participants to become comfortable with the audible prompts, presentation stimuli, task, and familiar with the scanning procedure. At the conclusion of this session, participants were scheduled for their fMRI scanning session.

Functional Imaging. Within two weeks, the participants attended the scanning session. Functional MRI was performed using a 3T Magneton Trio system (Siemens, Erlanger, Germany) fitted with a 12-channel head coil located at the McCausland Center for Brain Imaging, University of South Carolina at Palmetto Richland Memorial Hospital. Participants were supine on the table with their head immobilized using pillows and foam pads. The MRI scan lasted approximately 45 minutes and included: (1) one 21-second localizer (scout) to localize functional axial slices, (2) one 6-minute and 17 second high-resolution anatomical scan [sagittal T1-weight; repetition time: 2250 ms echo time 4.15 ms; one slab divided into 192 slices; slice thickness: 1 mm; flip angle: 9 degrees; field of view: 256 x 256 mm^2; voxel size: 1 x 1 x 1 mm^3; bandwidth 150 Hz per voxel; echo spacing: 9.4 ms], (3) three 10-minute and 51 second functional runs [ascending, interleaved, transversal; repetition time: 1550 ms; echo time: 34.0 ms; 42 slices; slice thickness: 3.00 mm; flip angle: 71 degrees; field of view: 216 x 216 mm^2;

voxel size: 3 x 3 x 3 mm^3; BOLD threshold: 4.00; bandwidth: 1984 Hz per voxel; echo spacing: 0.59 ms], (4) and one 6-minute and 10 second T2-weight resting state scan [descending, interleaved, transversal; repetition time: 1850 ms; echo time: 30 ms; 34 slices; slice thickness: 3.00 mm; flip angle: 75 degrees; field of view: 208 x 208 mm^2; voxel size: 3 x 3 x 3 mm^3; BOLD threshold: 4.00; bandwidth: 2004 Hz per voxel; echo spacing: 0.58 ms]. These scans were administered in the aforementioned order for all participants.

Conditions and Stimuli. The same arm rotation task from the MIQ-3 was used as the imagery stimulus because of its simplicity allowing subjects to control and reproduce the task. This task involved participants slowly extending their non-dominant hand straight out to their side so that it is parallel to the ground, palm down. They then moved their arm forward until it was directly in front of their body (still parallel to the ground). Experimental conditions included KI, IVI, and EVI, as well as a control condition that involved viewing a fixation cross. There were three scanning sessions with six repetitions for each experimental condition, resulting in 18 trials for each experimental condition. All conditions were randomized and counterbalanced across each run for each participant.

The experimental conditions (i.e., FEELING, INTERNAL Perspective, EXTERNAL Perspective, and REST) were presented in pseudo-randomized order (counterbalanced for condition) using Presentation software (NeuroBehavioral Systems, Inc., Berkeley, CA). All stimuli were projected onto a screen positioned behind the fMRI scanner that was seen by the participants through a mirror mounted onto the head coil. Each participant completed three functional scanning runs with a duration of ten minutes and thirty seconds each. Within each run, each participant completed 6 trials in each experimental condition. Each trial lasted twenty-three seconds and consisted of: i) an auditory cue indicating the participant should open their eyes, ii) a visual prompt to inform the participant of the imagery condition (3 seconds) and iii) a blank screen which was presented while the participants engaged in imagery (20 seconds). All participants were instructed to close their eyes after reading the imagery condition and to keep them closed for the duration of subsequent motor imagery. All control (rest) conditions required the participant to stare at a fixation cross in the middle of the screen. Individual trials were separated by a pseudo-randomly chosen temporal jitter of 150, 250, 350 or 450 milliseconds. Following the scanning session, participants completed a post-experiment debriefing questionnaire.

Data Analysis. All data was pre-processed using Statistical Parametric Mapping software (SPM8, Wellcome Trust Centre for Neuroimaging, London). Initially, motion correction in the functional images was completed using SPM realignment. This estimates six rigid-body transformation parameters for each image by finding the parameters that minimize the mean squared difference between it and a reference image. The structural T1-weighted scan was used as the reference image for each subject. This image was co-registered to the mean functional image. The functional and anatomical images were normalized to MNI space using trilinear interpolation method. The scans were smoothed using a Gaussian kernel set at 8 mm full width at half-maximum.

Statistical analyses were completed using a general linear model with separate model regressors for each task condition to describe the data through experimental effects. Six regressors were used (x, y, z, yaw, pitch, and roll). One sample *t*-tests were used to contrast the following experimental conditions: aggregated imagery conditions (KI, IVI, and EVI) minus rest, KI minus rest, IVI minus rest, EVI minus rest, KI minus IVI, KI minus EVI, IVI minus KI, IVI minus EVI, EVI minus IVI, and EVI minus KI. We also calculated the inverse contrasts of IVI minus EVI, KI minus EVI, and KI minus IVI. Comparisons of the functional data were assessed at the $p < 0.001$, uncorrected level. Activated clusters were considered significant if their spatial extent threshold was greater than 3 voxels. The results are presented at the cluster level (k) and peak t-value (local peak activation amplitude), with the associated MNI coordinates (See Figure 2.3 for Chronological Order of Experiment)

Results

Imagery Background

Frequency statistics indicated 68% (good imagers = 14; poor imagers = 11) of participants reported knowing what mental imagery is while 12 did not (good imagers = 4; poor imagers = 8). Those that did defined mental imagery as imagining or visualizing a task, object, or performance in their mind without moving; nine participants did not provide a definition. Overall, 16 participants had a positive attitude toward using imagery for developing skills and increasing successful performances, while nine participants had a neutral attitude and 10 participants did not provide a response. When asked if imagery was previously used for performance enhancement, more good imagers (n = 11) than poor imagers (n = 4) indicated that they had previously used mental imagery for sport, dance or injury rehabilitation.

Mental Chronometry and Imagery Ability Variation by Imagery Ability

Results of the MANOVA for 30-seconds of physical repetitions and KI, IVI, and EVI imagined repetitions of the MIQ-3 arm rotation task by imagery ability group was not significant, Pillai's Trace = 0.18, F (4, 32) = 1.80, $p > 0.05$, indicating that good imagers completed approximately the same amount of physical repetitions as did poor imagers. The multivariate analysis results for the MIQ-3 and VMIQ-2 scales by ability group were significant, Pillai's Trace = 0.87, $p < 0.001$, Eta = 0.89, with significant univariate analyses for the scales on each questionnaire favoring the good imagery group (Table 3.1).

Composite mean MIQ-3 scores were 81.17 ± 2.41 in the good imager group and 48.47 ± 8.42 in the poor imager group. Individual scale scores for the good imager group were: KI = 27.29 ± 0.89, IVI = 27.17 ± 0.86 and EVI = 26.72 ± 1.45. Poor imager mean scores were 17.79 ± 4.44 for KI, 15.63 ± 3.30 for IVI, and 15.05 ± 5.03 for EVI. Composite mean scores for the VMIQ-2 were also calculated. Overall, mean VMIQ-2 scores were 161.72 ± 15.61 for good imagers and 112.68 ± 23.89 for the poor imager group. Mean scores for the good imager group were: KI = 55.00 ± 5.26, IVI = 51.89 ± 8.37 and EVI = 54.83 ± 5.26. Poor imager mean scores were: KI = 38.58 ± 9.97, IVI = 33.32 ± 10.58 and EVI = 40.79 ± 10.46. Spearman’s rho correlation coefficients conducted to examine inter-scale correlations for the sample (n = 37) indicated significant correlations for all scale conditions (Table 3.2).

EMG Activity during Imagery Conditions

All EMG statistical computations were completed with raw EMG data. When considering EMG activity of the pectoralis major muscle and the anterior portion of the deltoideus muscle, separate repeated-measure ANOVAs for each condition did not reach significance across the three trials ($p > 0.05$). Consequently, an average EMGrms value was acceptable to be used for the remaining analyses. EMGrms independent samples t-tests for each imagery condition showed no significant muscle activity for either muscle ($p > 0.05$), precluding EMG regression from the fMRI analyses. Lastly, *t-tests* for mean differences between groups also were not found to be significant (p = 0.07 – 0.85) (Table 3.1).

fMRI Results

Of the 37 participants, 43.2% of the participants had previously undergone an MRI (n = 16) (e.g., knee, shoulder, ankle), but not necessarily of their brain. Nine of these participants were classified as good imagers and seven were classified as poor imagers.

On a 10-point Likert scale (1 = greatly to 10 = not at all), the debriefing questionnaire showed that two participants switched between imagery perspective (one good imager and one poor imager) and three participants (one good imager and two poor imagers) switched between imagery modality during the brain-imaging task (with a score less than five). As a result, their data was removed from any further data analysis. On a Likert scale (1 = not at all to 10 = greatly) most poor imagers were able to focus on each imagery perspective (Mean = 7.00 ± 1.60) and were able to focus on each imagery modality (Mean = 6.68 ± 1.83). On the same scale, all good imagers indicated that they were able to focus on each imagery perspective (Mean = 7.22 ± 1.26), while all but one good imager was able to focus on each imagery modality (Mean = 7.33 ± 1.65). Lastly, when asked to what extent they were able to focus on the task during scanning 16 poor imagers and 17 good imagers indicated that they were able to focus on the task during the scanning (rating of greater than 5).

Contrasts across Good and Poor Imagers

In order to assess gross differences in neural recruitment between the two groups during imagery in general, we first compared good and poor imager groups for all imagery abilities (KI + IVI + EVI – Rest) with a two-sample t-test, peak activations were found in the left cingulate gyrus and right middle cingulum (Figure 3.4). Significant differences were also found when rest was subtracted from KI in the left caudate nucleus (Figure 3.5), and when rest was subtracted from EVI in the left precentral gyrus and SMA, and the right lingual gyrus and cerebellum (Lobule VIII) (Figure 3.6). No significant differences between good and poor imager groups were found for the IVI minus rest contrast.

The two-sample t-test IVI – KI only revealed one significant difference between good and poor imagers in the right inferior frontal orbicularis (Figure 3.7). However, the EVI – KI comparison showed the most differences between the groups, including the left precentral and postcentral gyri, SMA, pallidum and putamen, and the right caudate nucleus, putamen, insula, middle and superior frontal orbicularis, pallidum, postcentral gyrus and heschl gyrus (Figure 3.8). All other two-sample t-tests between good and poor imagers did not present with significant differences.

Significant mean differences in activation were also found when the poor imager group was compared to the good imager group. The KI minus IVI contrast showed peak activation differences in the right inferior frontal orbicularis between the groups (Figure 3.9). Significant differences were also found when EVI was subtracted from KI in the left thalamus, precentral gyrus, pallidum, putamen and postcentral gyrus, and the right caudate nucleus, putamen, insula, pallidum, postcentral gyrus, middle frontal orbicularis and heschl gyrus (Figure 3.10). Lastly, there was a mean activation difference in the left middle cingulum was significant between the good and poor imagery groups when KI was subtracted from EVI (Figure 3.11). All other two-sample t-tests comparing the poor imager group to the good imager group failed to yield significant differences.

Contrasts across Imagery Conditions and Rest

When the rest condition was subtracted from all of the imagery conditions (KI, IVI, and EVI), both groups showed activations of the left middle frontal gyrus, inferior frontal orbicularis, inferior and superior parietal lobule, and insula. On the right side of the brain, significant peak activations were found in the inferior frontal opercularis, frontal rolandic operculum, superior temporal gyrus, and postcentral gyrus. In the good imager group, activations were also observed bilaterally in the middle temporal gyrus and precentral gyrus. Additional peak activations were found in the right middle frontal gyrus, inferior frontal orbicularis, inferior temporal gyrus, inferior and superior parietal lobules, inferior occipital cortex and cerebellum (Lobule VI and Crus I), and the left frontal rolandic operculum, superior frontal gyrus, middle frontal orbicularis, inferior frontal triangularis, temporal rolandic operculum, superior temporal pole, SMA and hippocampus. In the poor imager groups, peaks of activation were located in the left inferior frontal opercularis, superior temporal gyrus, precuneus and cerebellum (Lobule IV and V), and the right supramarginal gyrus, putamen and insula (Table 3.3).

The contrast between KI and the rest condition (KI minus rest) for the good imager group showed greater expected significant activations in the left SMA, middle frontal gyrus and putamen, the right inferior frontal opercularis and cerebellum (Crus I), and the inferior frontal orbicularis bilaterally. Although the poor imager group had significant activations in some of these same areas (i.e., left SMA and bilateral inferior frontal orbicularis), their peak activation level was less than the good imager group. Additional peak activations shared by the good imager and poor imager groups included the left inferior parietal lobule and right insula. The good imager group also showed peak activations bilaterally in the middle and inferior temporal gyri and calcarine, the right superior temporal gyrus, inferior parietal lobule, postcentral gyrus, and left thalamus. Additional activations for the poor imager group were found in the left inferior frontal opercularis, superior temporal gyrus, precuneus, superior parietal lobule and cerebellum (Lobule IV and Lobule V), the right frontal rolandic operculum, supramarginal gyrus, precentral gyrus, and the pallidum bilaterally (Table 3.4).

When the rest condition was subtracted from IVI, both groups showed activation bilaterally in the superior temporal gyrus, the right inferior frontal opercularis, middle temporal gyrus, and the left inferior parietal lobule, SMA and insula. In the good imager group, activations were also observed bilaterally in the inferior frontal orbicularis and superior parietal lobule. The left inferior frontal triangularis, middle frontal orbicularis, superior temporal pole, middle and inferior temporal gyri, temporal rolandic operculum and precentral gyrus, and the right postcentral gyrus, insula and cerebellum (Lobule VI) also showed peak activations in the good imager group. In the poor imager group, peaks of activation were located in the middle frontal gyrus and pallidum bilaterally, the left inferior frontal opercularis and cerebellum (Lobule IV and V), and the right frontal rolandic operculum, superior temporal pole and supramarginal gyrus (Table 3.5).

Finally, when the rest condition was subtracted from EVI significant activation sites were found in the right inferior frontal opercularis and supramarginal gyrus, and the left inferior parietal lobule and precentral gyrus for both the good imager and poor imager groups. Additional activation in the good imager group was found in the inferior frontal orbicularis, middle frontal gyrus, and middle temporal gyrus bilaterally. The good imager group also presented peak activations in the left inferior frontal triangularis, middle frontal orbicularis, SMA, middle occipital gyrus and putamen, and the right superior temporal gyrus, superior temporal pole, superior and inferior parietal lobule, precentral and postcentral gyri, inferior occipital gyrus, cerebellum (Lobule VI) and insula compared to the poor imager group. Although the poor imager group showed less activations for EVI when compared to rest, there were significant activations located in the superior frontal gyrus bilaterally, and the left superior parietal lobule and calcarine (Table 3.6).

Contrasts across Imagery Conditions

When EVI was subtracted from KI, both groups had peak activations in the right SMA. For the good imagery group, additional peak activations were only found in subcortical areas (i.e., vermis (III) and thalamus) when compared to poor imagers. Compared to the good imager group, the poor imager group showed an increased number of peak activation sites in the supramarginal gyrus bilaterally, as well as the left inferior frontal triangularis, middle frontal gyrus, SMA, lingual gyrus, cerebellum (Lobule IX) and middle cingulum, and the right superior, inferior and middle temporal gyri, insula and cerebellum (Lobule VI, Lobule VIII, and Crus I) (Figure 3.7). When IVI was subtracted from KI, the good imager group presented significant activation in the left superior frontal gyrus, inferior parietal lobule, SMA and hippocampus, and the right caudate nucleus and cerebellum (Lobule VIIb and VIII) (Table 3.8). For the same contrast, the poor imager group showed peak activations mostly in the frontal cortex (i.e., left inferior frontal triangularis, middle frontal orbicularis and superior frontal gyrus, and bilateral inferior and superior frontal orbicularis), as well as the left supramarginal gyrus, pallidum and middle cingulum, and the right cerebellum (Crus II) (Table 3.8).

When KI was subtracted from IVI, no significant activations were present for the good imagery group or the poor imager group. However, when EVI was subtracted from IVI, significant activations were only found in the right SMA for the good imager group. In the poor imager group, peak activations were found in the left cuneus and caudate nucleus bilaterally (Table 3.9).

When IVI was subtracted from EVI in the poor imager group, no significant activations were present. However, when IVI was subtracted from EVI in the good imager group, peak activation was found in the left inferior parietal lobule (Table 3.10). When KI was subtracted from EVI, the good imager group showed activations bilaterally in the precentral gyrus. Peak activations were also found in the right middle frontal gyrus, superior and inferior temporal gyri, inferior parietal lobule, supramarginal gyrus and paracentral lobule, and the left middle temporal gyrus and postcentral gyrus compared to the poor imager group. Although the contrast of KI subtracted from EVI showed less activation for the poor imager group, there were significant activations located in the right middle occipital gyrus and insula compared to the good imager group (Table 3.11).

Discussion

Extending the preliminary biological evidence of intra-individual variability in neural network activity associated with the MIQ-3 protocol, this was the first study comparing real-time inter-individual differences among participants screened as having good and poor imagery abilities by the MIQ-3. This line of biological validation of KI, IVI and EVI constructs are essential to advance both the behavioral and neuroscience literature because at least three theoretical models currently guide research in these disciplines. Prior to examining neural activity differences, we established that our MIQ-3 screened participants also reported significantly different KI, IVI and EVI scores on the VMIQ-2 (Table 3.1). Psychometrically, the VMIQ-2 means favoring the good imagery group, the MIQ-3 and VMIQ-2 inter-scale correlations of this sample ($n = 37$) and those (n = 206) reported in Seiler et al. (in review) are evidence of convergent validity.

Controlling for temporal equivalence of imagining and physically performing the task through mental chronometry and muscular activity EEG data were unique aspects of our study and aligned with the recommendations of Guillot et al. (2008, 2009). Finding no intra- or inter-individual differences in these variables precluded statistical control in subsequent modeling analyses of neural activity data. In order to establish common neural network areas during imagery in general, brain regions and specific areas were compared to rest through the cognitive subtraction method (Petersen et al., 1989). Rest minus the aggregated imagery abilities (KI, IVI, and EVI) indicated that both the good imagery group and poor imagery group presented peak activations in the inferior parietal lobule as well as motor-related regions (i.e., SMA, cerebellum, and insula). Consistent with previous research and our hypotheses, this pattern of activation overlaps, although not completely, those associated with motor imagery properties (Decety et al., 1997; Gerardin et al., 2000; Grafton et al., 1996; Lotze et al., 1999; Stephan et al., 1995; Malouin et al., 2003; Boecker et al., 2002; Halpern & Zatorre, 1999). Also consistent with our hypotheses, activation was found in the inferior frontal regions which are associated with movement inhibition properties. Although inconsistent with our hypothesis, a large amount of temporal region activation was also found that is associated with visual motion processing and observation of movement.

In order to capture regions and areas in which BOLD signal differentiated between imagery type, activity differences in location and intensity during KI, IVI, and EVI were compared to rest separated for each imagery ability group. Extending previous work limited to IVI (Guillot et al., 2008, 2009), the focus of activation when KI was compared to the rest condition was equal across the good imager and poor imager groups partially confirming our hypothesis; peak activation during KI was in the inferior frontal regions (i.e., inferior frontal opercularis and inferior frontal orbicularis), inferior parietal lobule, SMA, cerebellum, and putamen for both good and poor imager groups. Such activations, especially in the inferior parietal lobule and inferior frontal regions are consistent with previous research indicating their role in generating motor images (Gerardin et al., 2000; Kapur et al., 1994; Lafleur et al., 2002; Lotze & Halsband, 2006; Meister et al., 2004; Ranganath, Johnson, & D’Esposito, 2003; Rama et al., 2001; Sun et al., 2005). Additionally, good imagers recruited several areas in the temporal cortex and also the occipital cortex (i.e., calcarine: location of the primary visual cortex) compared to poor imagers. The additional areas active in the temporal cortex for good imagers is not consistent with previous research (Guillot et al., 2008; Jiang et al., in press), with the primary functions of these areas associated with auditory and visual motor processing.

Conversely, the poor imagers had more activation in the parietal cortex areas (i.e., precuneus, supramarginal gyrus, superior parietal gyrus, and postcentral gyrus) and the pallidum compared to the good imagers. Although these findings are inconsistent to the areas expected to be activated by KI, it suggests that poor imagers are using an increased amount of brain areas while imagining a movement. These differences may be the result of poor imagers relying on working memory (Catalan, Honda, Weeks, Cohen, & Hallet, 1998; Yoo, Paralkar, & Panych, 2004; Rama et al., 2001; Tsukiura et al., 2001) to create the image or planning of the motor action (Cavanna & Trimble, 2006;

Kawashima, Roland, & O'Sullivan, 1995; Meister et al., 2004). Furthermore, the activation of the precuneus in this contrast is surprising because it is associated with internally represented visual images (Oshio et al., 2010), not KI.

When directly comparing IVI to the rest condition, expected activation in the inferior parietal lobule and SMA was found in both good and poor imager groups. Also consistent with our hypothesis, good imagers showed peak activation in the superior parietal regions (superior parietal and postcentral gyri). However, inconsistent results were also found for both the good imager (i.e., inferior frontal region, temporal cortex, precentral gyrus, insula, and cerebellum) and poor imager (i.e., middle frontal gyrus, middle and superior temporal gyri, supramarginal gyrus, pallidum, and cerebellum) groups. Although the good imager group activated the expected dorsal visual stream, the amount of activity found in the good imager group was also more widespread compared to the poor imager group. This is unlike the previous study comparing good and poor imagers by Guillot et al. (2008), indicating that good imagers had an efficient neural network of greater activation in the parietal and premotor regions, while poor imagers recruited more areas in the oribto-frontal and cingulate cortices as well as the cerebellum.

Lastly, we subtracted the rest condition from EVI and examined the peak activation between the good and poor imager groups, which revealed the greatest difference in peak brain activity between the groups. Consistent with our hypothesis, we found peak activations in the inferior and superior parietal lobules, postcentral gyrus, SMA, and occipito-temporal cortex for the good imager group. However, other expected areas of the visual stream (i.e., precuneus, cingulate gyrus and frontopolar cortex) as well as the premotor cortex were not found to be activated. In the poor imager group, activations consistent with our hypothesis were only found in the superior and inferior parietal lobules and calcarine, while additional activations were found in the superior frontal, supramarginal and precentral gyri. Although we expected a limited number of activation areas with increased intensity for the good imager group, we found the opposite with this group having a broader distributed neural network including brain areas associated with visual mental imagery, motor planning, and working memory which reflect participants' brain activity when retrieving and producing the mental image. Specifically, the increased activation in the putamen has strong reciprocal connections with the caudate nucleus involved in integrating spatial information with motor behavior formation, while may also assist in controlling motor preparation (Alexander & Crutcher, 1990) and tasks (DeLong et al., 1984) as well as movement sequences (Marchand et al., 2008). Although EVI is only being compared to a rest condition, this has been the only contrast to show peak activation in true occipital areas (i.e., inferior and middle occipital gyri). Many studies have reported that EVI is considered a truer form of VI (Hall, Rodgers, & Barr, 1990; Janssen & Sheikh, 1994; White & Hard, 1995) relying on visuospatial processing (Mahoney & Avener, 1977) suggesting that such activations in the occipital cortex, putamen and insula should be expected.

When mean differences for EVI between the good imager group and the poor imager group was contrasted to the rest condition, the focus of activation was increased in the motor and sensorimotor areas for the good imager group. Such activity in motor areas may be attributed to a greater, or possibly the equivalent amount, neural effort needed to imagine the arm rotation task. Although both groups may have activated these areas, the average difference between the good group and the poor group was truly significant revealing that they may be better at separating and engaging in EVI.

Differences between good and poor imagers during each imagery ability condition were further elucidated by examining overall activation areas to rest between good and poor imagers revealed indicating greater activation in the frontal, parietal and premotor regions known to be associated with motor imagery (Decety et al., 1997; Gerarding et al, 2000; Grafton et al., 1996) for the good imager group. In contrast, poor imagers recruited more subcortical regions (e.g., cerebellum and pallidum) and the middle frontal gyrus, suggesting that they had difficulty retrieving the movement in working memory and eliciting a mental representation of this movement (Duzel et al., 2001; Leung, Gore, & Goldman-Rakic, 2002; Pochon et al., 2002; Ruggs, Fletcher, Frith, Frackowiak, & Dolan, 1996; Tulving et al., 1994; Zhang, Leung, & Johnson, 2003).

Consistent with our hypothesis, the good imager group had peak activation in most of the predicted brain areas (i.e., inferior parietal lobule, SMA, caudate nucleus, and cerebellum) when IVI was subtracted from KI, suggesting that these areas are part of a neural network that produces KI (Guillot et al., 2009). Again, however, the poor imagers were found to have increase of activity in the frontal cortex, as well as other areas not related to MI (i.e., supramarginal gyrus and middle cingulum), suggesting that poor imagers are dependent on a more widely distributed neural network when engaging in imagery. However, inconsistencies were found when the poor imager group was compared to the good imager group (isolating the activity recorded only by poor imagers) for KI minus IVI. This contrast showed that poor imagers were found to have greater activation in the inferior frontal orbicularis. The increased activation in the inferior frontal orbicularis has strong connections to working memory (Ranganath, Johnson, & D'Esposito, 2003; Kapur et al., 1994) and the subsystems that store and manipulate visual images but not those involved in KI.

Investigating the activation areas during KI compared to EVI for good and poor imagers showed poor imagers to have a larger pattern of activation. Compared to the good imager group only having significant activation in the SMA and thalamus, the poor imager group had various peak activations in the frontal, temporal and parietal cortices, as well as the cerebellum. Although the SMA was expected to have increased activation during KI for good imagers, our results were inconsistent with our hypothesis for other areas being activated associated with KI (i.e., inferior parietal lobule, inferior frontal areas, putamen, caudate nucleus, and cerebellum). Additional peak activations by the poor imager group were found when EVI was subtracted from KI compared to the good imager group. Although there was more active brain regions, only two (i.e., caudate nucleus and putamen) have been associated with KI, reflecting poor imagers' need to have an extensively activated brain network to create mental images compared to good imagers.

Inconsistent with our hypothesis that IVI would elicit greater activity in the dorsal visual stream, results indicated that only good imagers recruited the SMA known to be associated with motor planning/control (Bischoff-Grethe, Goedert, Willingham, & Grafton, 2004; Perry et al., 1999; Schubotz & von Cramon, 2001, 2002), movement preparation (Jenkins, Jahanshahi, Jeuptner, Passingham, & Brooks; Stephan et al., 1995), movement initiation (Jenkins, Jahanshahi, Jeuptner, Passingham, & Brooks, 2000, and motor imagery (Boecker et al., 2002; Halpern & Zatorre, 1999; Malouin, Richards, Jackson, Dumas, & Doyon, 2003; Halpern & Zatorre, 1999) compared to the poor imager group. This is also inconsistent with previous studies illustrating the similarity in brain activity when participants engage in MI of a movement task (Lotze et al., 1999).

Moreover, when directly comparing group means for IVI to the other imagery abilities (KI and EVI) we only found that good imagers had greater mean activation in the inferior frontal orbicularis compared to poor imagers, which is known to play a role in movement inhibition (Aron, Robbins, & Poldrack, 2004). Although some results are similar to Guillot et al. (2008 (i.e., SMA and frontal regions), their study only instructed participants to imagine their task using the first-person perspective compared to a rest and physical condition, not the other imagery abilities. Results may be explained by task type differences (finger-sequence task versus gross motor movement) and the inconsistency in our imagery screening methods (global imagery score versus MIQ-3 subscale scores).

Distinct neural contributions of EVI for good and poor imagers in relation to the other imagery abilities have yet to be proposed. Although research has found that different VI perspectives can cause different effects on motor learning and motor performance (e.g., Hardy & Callow, 1999) and that distinct brain areas underlie the two

VI perspectives (Guillot et al., 2009; Jiang et al., in press), our results did not support this. When IVI was subtracted from EVI, the only remaining brain area to be significantly activated solely by EVI was located in the inferior parietal lobule only for the good imagers which has been associated with both VI and KI abilities. Because of this lack in peak activation we suggest two ideas: 1) both good imagers and poor imagers use the same neural network for EVI in comparison to IVI, and 2) there is a large overlap in brain areas activated by both EVI and IVI particularly for this simple, upper body arm rotation task. Nevertheless, our results support and provide neuroscientific evidence to a recent narrative by Callow and Roberts (2012) negating that different imagery perspectives exist.

When EVI was compared to KI, a larger distinction in brain activity was found between the good imagery group and poor imager group; however, peak activations did not follow expected patterns indicated in our hypothesis. Instead, the good imager group activated areas not associated with EVI (i.e., middle frontal gyrus, middle temporal gyrus, postcentral gyrus, supramarginal gyrus, precentral gryus, and paracentral lobule), but rather areas associated with motor learning (e.g., Grafton, Salidis, & Willingham, 2001; Penhune & Doyon, 2005; van Mier, Perlmutter, & Petersen, 2004), working memory and memory retrieval (e.g.,Duzel et al., 2001; Pochon et al., 2002; Zhang, Leung, & Johnson, 2003), kinesthetic perception (Bodegard et al., 2003; Naito, 2004; Naito, Roland, & Ehrsson, 2002), and motor imagery (Munzert, Zentgraf, Stark, & Vaitl, 2008; Porro et al., 1996; Sharma, Jones, Carpenter, & Baron, 2008; Tomasino, Werner, Weiss, & Fink, 2007). In contrast, poor imagers were only found to recruit the middle occipital gyrus and insula, possibly reflecting their lack of ability in distinguishing separate imagery abilities when instructed to only engage in one specific imagery ability.

When mean group differences between good and poor imagers were compared for EVI minus KI, the middle cingulum was found to be significantly activated when comparing poor imagers to good imagers. This activity is inconsistent with our hypothesis and is of interest because the same area was significantly activated when good imagers were compared to poor imagers when EVI was subtracted from KI. However, this appears to only reflect the significant difference between the groups in the middle cingulum with good imagers still revealing greater activation, not necessarily the direction of the difference. There was a similar outcome for poor imagers compared to good imagers when KI was subtracted from EVI. Both groups activated the similar areas except for one area that the good imagers manifested greater activation in compared to the poor imager group, the superior frontal orbicularis. Independent of the comparison, good imagers still produced greater activation in all activated areas compared to poor imagers. Such activation can be explained by good imagers using working memory to produce the mental image (Ranganath, Johnson, & D’Esposito, 2003; Kapur, 1994) or inhibiting motor movement (Vollm et al., 2006; Del-Ben et al., 2005).

Given that the brain activity found for the imagery abilities had some distinctions, we provide central evidence that the different imagery modalities delineated in the MIQ-3 reflect those defined in the sport science literature (Guillot et al., 2009). However, because data regarding IVI and EVI are inconsistent with a recent study by Jiang et al. (in press) additional examination of these imagery abilities is suggested to determine if they have truly distinct or overlapping neural networks. Moreover, our data does not show consistent increased intensity for the good imagery group in the predicted neural networks developed from previous literature (Binkofski et al., 2000; Guillot et al., 2008, 2009; Jiang et al., in press; Solodkin et al., 2004), suggesting that the MIQ-3 was not effective in separating good imagers from poor imagers. Therefore, imagery ability questionnaires may need to be combined with other measures to truly distinguish between a group of good imagers from poor imagers as previously utilized by Guillot et al. (2008). To further overcome these inconsistencies, and given that imagery remains an important moderator in motor learning and performance, future studies should further examine the neural activity of good and poor imagers distinguished solely by self-report imagery ability questionnaires.

The present findings provide initial evidence regarding the neural activity found across imagery abilities in good and poor imagers. Although our results are inconsistent with previous studies, those either did not investigate the neural substrates involved in all imagery abilities or only examined participants with good imagery abilities (Binkofski et al., Guillot et al., 2008, 2009; Lotze et al., 2003; Solodkin, 2004). Moreover, Guillot et al. (2008) reported that good imagers showed greater activations in the parietal and premotor areas during the imagined performance of a finger sequence task than poor imagers. Such activations may be explained by the fact that in their experiment, the participants were required to learn a specific sequence of movement coordinating the use of small muscle movements. Thus, it is possible that such task characteristics (e.g., speed and learning a movement sequence) required increased brain activation because of the motor sequencing/planning and motor learning involved to complete the task. Therefore, future replicative investigations should consider a broader range of tasks perhaps comparing neural activity across the four MIQ-3 movements.

The following limitations of the current study are warranted. First, we restricted our study to only female participants. Therefore, the present results may only represent the neural patterns of females when engaging in different types of imagery and cannot be generalized to males. We suggest that future studies should consider whether similar or different brain activity will occur in a sample of male participants, thought to have performance advantages for imagery tasks involving spatial abilities (Berthoz & Viaud-Delmon, 1999; Campos, Perez-Fabello, & Gomez, Juncal, 2004; Parsons et al., 2004; Siegel-Hinson & McKeever, 2002). In addition, we required the participants to close their eyes when engaging in the imagery task. Previous studies have shown that the eyes-open and eyes-closed states may produce some variations in the underlying neural activity found in the visual and visual-related regions, and that some may go undetected (Marx et al., 2004). Therefore, future studies should have participants engage in MI with their eyes-open or eyes-closed, as well as having their eyes-open or eyes-closed during the rest condition to examine if there are differences in activations/deactivations for different brain regions, especially in the occipital cortex for the VI conditions. Overall, our findings in part support Paivio's (1985) assertion that imagery ability has a biological (genetic) basis, and the central idea of theoretical models proposing various performance-related relationships that are mediated or moderated by imagery abilities.

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Table 3.1

Descriptive Statistics for MIQ-3 Screened Ability Groups

	Good Imagery Ability (n = 18)		Poor Imagery Ability (n = 19)			
	X	SD	X	SD	*F*	T-Value
Physical Repetitions (in 30 s)	7.44	2.38	7.58	2.09	*0.03*	
Imagery Repetitions (in 30 s)						
KI	7.04	2.36	5.98	2.09	*2.07*	
IVI	7.59	2.76	6.12	1.83	*3.68*	
EVI	7.30	2.64	5.82	2.02	*3.66*	
MIQ-3 Scores						
KI	6.82	0.19	4.45	0.19	*78.98**	
IVI	6.79	0.16	3.99	0.16	*150.02**	
EVI	6.68	0.22	3.76	0.22	*89.81**	
VMIQ-2 Scores						
KI	4.32	0.19	2.78	0.18	*34.83**	
IVI	4.57	0.17	3.40	0.16	*25.14**	
EVI	4.58	0.16	3.23	0.16	*36.31**	
Raw EMGrms (mV in 30 s)**						
Pectoralis Major						
Physical	244.56	501.49	22.46	13.42		-1.88
KI	17.59	36.75	9.92	10.55		-0.87
IVI	16.66	31.59	9.27	8.00		-0.99
EVI	16.59	29.03	7.84	2.05		-1.28
Deltoidius (anterior portion)						
Physical	236.06	274.69	132.22	142.55		-1.43
KI	20.11	2.48	19.04	0.23		-1.82
IVI	20.01	2.34	18.97	0.23		-1.93
EVI	19.95	2.21	19.05	0.60		-1.66

Note. *$p < 0.01$ (2-tailed), ** $p > 0.05$

Table 3.2

MIQ-3 and VMIQ-2 Inter-Scale Correlations for Screened Ability Groups

		VMIQ-2		
		KI	IVI	EVI
MIQ-3	KI	.64*	.59*	.80*
	IVI	.78*	.71*	.73*
	EVI	.73*	.61*	.66*

Note. *$p < 0.01$ (2-tailed)

Table 3.3

Brain Areas Significantly Activated during All Imagery Conditions Compared to Rest for Good and Poor Imagers

		Good Imagers					Poor Imagers				
Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]
		X	Y	z	k		x	y	z	k	
Frontal Cortex											
Frontal Mid	L	-42	38	30	205	5.17	-24	-4	50	3770	10.68
		-46	30	32	205	4.97					
	R	42	48	24	3	3.89					
Frontal Inf Oper	R	58	12	12	384	4.58	56	10	18	311	4.86
	L						-60	8	18	122	4.70
Rolandic Oper	L	-50	6	14	860	6.53					
		-48	4	2	860	5.80					
	R	60	8	30	8	4.16	50	8	4	311	4.53
		60	4	12	26	3.84	56	14	0	311	4.41
							56	2	40	32	4.06
Frontal Inf Orb	L	-40	44	-16	28	5.36	-44	46	-14	21	3.96
		-50	38	-6	44	3.75	-46	38	-14	21	3.81
	R	50	38	-10	384	4.65					
Frontal Sup	L	-24	-8	52	7365	8.73					
		-18	68	10	4	4.00					
Frontal Mid Orb	L	-40	54	-12	28	4.00					
		-46	46	-2	44	4.41					
		-26	52	-12	4	3.94					
Frontal Inf Tri	L	-38	28	30	205	4.64					
Temporal Cortex											
Temporal Sup	L						-50	6	-2	122	4.15
	R	68	-30	10	23	4.08	60	-36	24	28	4.07
		68	-32	18	23	4.01					
Temporal Mid	R	44	-42	8	294	8.23					
		62	-44	12	294	4.49					
		56	-70	6	82	4.29					

	L	-52	-54	12	3731	7.09					
Rolandic Oper	L	-48	6	16	1369	6.81					
Temporal Pole Sup	L	-48	10	0	1369	5.93					
Temporal Inf	R	58	-64	-2	82	4.53					
		50	-20	-18	28	4.18					
Parietal Cortex											
Parietal Inf	L	-40	-42	56	3731	7.66	-40	-46	56	3770	4.84
							-48	-44	62	3770	4.56
	R	36	-46	48	810	6.17					
Supramarginal	R						40	-30	40	367	5.64
Postcentral	R	30	-32	56	230	4.57	34	-36	50	367	4.19
Parietal Sup	L	-24	-66	62	3731	7.99	-34	-60	66	22	4.35
	R	28	-46	60	810	4.79					
		16	-66	58	184	5.97					
Precuneus	L						-14	-66	66	18	4.31
Motor/Premotor Cortex											
Supp Motor Area	L	-6	-4	64	7365	12.20					
		-6	-8	72	7365	11.81					
Precentral	L	-58	-4	32	1369	5.15					
	R	60	10	30	384	4.78					
Occipital Cortex											
Occipital Inf	R	48	-76	-10	82	4.26					
Subcortical Areas											
Putamen	R						28	0	54	3770	6.78
Insula	R						34	18	4	105	5.07
	L	-30	18	8	36	4.12	-30	16	8	38	4.46
Cerebellum (IV & V)	L						-4	-48	-10	17	4.37
Cerebellum (VI)	R	38	-60	-24	230	6.69					
Cerebellum (Crus I)	R	36	-78	-22	7	4.37					
Hippocampus	L	-22	-14	-20	5	3.91					

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p <$ 0.001 level.

Table 3.4

Brain Areas Significantly Activated during KI Compared to Rest for Good and Poor Imagers

		Good Imagers					Poor Imagers				
Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]
		x	Y	z	k		x	y	z	k	
Frontal Cortex											
Frontal Inf Oper	L						-60	8	18	518	8.27
	R	58	12	14	26	4.12					
Rolandic Oper	R						48	8	10	863	4.90
Frontal Inf Orb	L	-40	44	-16	26	5.77	-42	46	-12	109	4.56
		-46	44	-2	56	4.31	-46	38	-14	109	4.01
	R	52	28	-2	36	4.04	-38	34	-12	109	3.93
		50	38	-10	15	4.03					
Frontal Mid	L	-36	38	26	202	5.36					
		-38	28	32	202	4.38					
Temporal Cortex											
Temporal Sup	L						-52	6	-2	518	4.88
	R	68	-30	22	3	3.87					
Temporal Mid	R	46	-44	8	92	5.43					
		56	-70	6	3	3.96					
	L	-50	-30	-12	216	6.37					
Temporal Inf	R	50	-18	-22	9	4.00					
	L	-54	-26	-18	216	4.82					
		-46	-16	-26	216	4.55					
		-44	-4	-26	9	3.86					

Parietal Cortex											
Parietal Inf	L	-44	-40	48	2272	5.92	-54	-36	50	1336	7.10
							-48	-44	62	1336	6.25
	R	36	-44	46	235	4.35					
Precuneus	L						-14	-64	68	25	4.56
Supramarginal	R						66	-30	30	82	4.24
							60	-36	26	82	4.17
Parietal Sup	L						-32	-62	66	7	4.00
Postcentral	R	28	-46	58	235	4.06					
Motor/Premotor Cortex											
Supp Motor Area	L	-6	-4	66	5721	11.32	-6	0	68	3898	6.98
Precentral	R						58	10	20	863	4.91
Occipital Cortex											
Calcarine	L	-24	-68	62	2272	7.85					
	R	16	-66	64	72	4.76					
Subcortical Areas											
Pallidum	R						24	-2	48	3898	6.95
	L						-16	0	-2	33	4.16
Insula	R	48	14	-2	36	3.95	36	16	4	863	5.83
Cerebellum (IV & V)	L						-6	-48	-12	3	3.73
Cerebellum (Crus I)	R	36	-78	-22	17	4.68					
Putamen	L	-30	-10	52	5721	9.63					
Thalamus	L	-14	-12	64	5721	9.18					

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Table 3.5

Brain Areas Significantly Activated during IVI Compared to Rest for Good and Poor Imagers

		Good Imagers					Poor Imagers				
Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]
		X	Y	z	k		X	y	z	k	
Frontal Cortex											
Frontal Mid	L						-24	-4	50	3422	9.98
	R						34	18	6	87	5.50
Frontal Inf Oper	R	58	14	12	40	4.31	56	10	16	351	4.87
		58	14	30	13	4.24					
	L						-54	8	14	47	4.13
Rolandic Oper	R						50	8	4	351	4.64
Frontal Inf Orb	R	50	38	-10	65	4.62					
	L	-40	44	-16	19	4.19					
		-42	44	-2	5	3.80					
Frontal Inf Tri	L	-40	38	28	93	4.38					
		-46	30	30	93	4.32					
Frontal Mid Orb	L	-36	56	-12	19	4.20					
Temporal Cortex											
Temporal Pole Sup	R						56	14	-2	351	5.00
	L	-50	10	-4	1142	5.99					
Temporal Sup	R	68	-30	14	16	4.31	60	-36	24	70	4.59
	L	-56	-44	20	2570	6.65	-52	6	-2	47	4.05
Temporal Mid	R	46	-44	8	196	6.51	52	-74	4	3	3.99
		62	-44	12	23	4.57					
	L	-52	-58	12	2570	6.96					
		-50	-30	-12	259	5.82					
		-60	-22	2	10	4.00					
Rolandic Oper	L	-48	6	16	1142	6.88					
Temporal Inf	L	-60	-62	-6	13	4.35					
Parietal Cortex											
Supramarginal	R						40	-32	42	401	6.06

Parietal Inf	L	-58	-30	44	10	3.90	-40	-46	56	725	4.99
							-46	-28	46	725	4.92
Precuneus	L						-14	-66	66	17	4.29
Parietal Sup	L	-24	-66	64	2570	8.17					
	R	18	-66	56	94	4.88					
Postcentral	R	64	-6	28	24	4.34					
Motor/Premotor Cortex											
Supp Motor Area	L	-2	2	60	6667	10.93	-6	0	60	3422	6.18
		-6	-4	64	6667	10.17					
		-6	-6	72	6667	10.03					
Precentral	L	-58	-4	30	1142	4.89					
Subcortical Areas											
Pallidum	R						22	-4	48	3422	7.19
							22	0	4	25	4.12
	L						-22	-4	4	18	4.08
Cerebellum (IV & V)	L						-4	-48	-10	17	4.55
Insula	L	-30	18	8	31	4.14	-30	16	8	28	4.43
	R	46	14	-20	15	3.91					
		48	14	-2	4	3.80					
Cerebellum (VI)	R	38	-60	-24	192	6.42					

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Table 3.6

Brain Areas Significantly Activated during EVI Compared to Rest for Good and Poor Imagers

		Good Imagers					Poor Imagers				
Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]
		x	Y	Z	k		x	y	z	k	
Frontal Cortex											
Frontal Sup	L						-24	-4	52	3032	9.43
	R						26	-2	54	3032	6.34
Frontal Inf Oper	R	58	12	14	336	4.68	56	10	20	9	4.00
		48	14	0	278	4.08					
Frontal Inf Orb	R	48	38	-12	104	4.79					
	L	-40	42	-16	22	5.04					
Frontal Inf Tri	L	-38	28	28	149	4.79					
Frontal Mid Orb	L	-40	44	-2	33	4.45					
Frontal Mid	L	-44	36	32	149	4.96					
	R	44	48	22	7	3.94					
Temporal Cortex											
Temporal Mid	L	-52	-56	14	3450	7.23					
		-60	-20	0	77	4.73					
	R	56	-70	6	217	4.31					
Temporal Sup	R	38	-34	14	372	4.80					
		60	-44	14	372	4.65					
Temporal Pole Sup	R	44	14	-20	278	5.02					
Parietal Cortex											
Parietal Sup	L						-36	-58	66	362	4.51
	R	16	-64	56	244	7.74					
		30	-50	64	992	5.00					

Parietal Inf	L	-36	-44	52	3450	8.53	-40	-46	56	362	4.39
		-44	-40	48	3450	8.10					
	R	36	-44	46	992	6.83					
		38	-36	48	992	6.61					
Supramarginal	R	56	-28	48	23	4.44	42	-32	42	84	4.39
Postcentral	R	62	-6	32	336	4.83					
Motor/Premotor Cortex											
Precentral	L	-32	-10	54	9366	8.97	-50	0	36	14	3.90
	R	60	4	24	336	5.84					
Supp Motor Area	L	-2	-6	66	9366	13.60					
		-2	0	58	9366	12.74					
Occipital Cortex											
Calcarine	L						-16	-66	66	3	3.89
Occipital Inf	R	48	-80	-4	217	4.53					
Occipital Mid	L	-46	-76	2	36	4.24					
Subcortical Areas											
Cerebellum (VI)	R	38	-58	-24	234	7.97					
Insula	R	48	6	-18	278	4.35					
Putamen	L	-32	-12	16	28	5.61					

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Table 3.7

Brain Areas Significantly Activated during KI Compared to EVI for Good and Poor Imagers

		Good Imagers					Poor Imagers				
Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]
		x	Y	Z	k		x	y	z	k	
Frontal Cortex											
Frontal Inf Tri	L						-42	32	12	233	5.68
Frontal Mid	L						-36	32	38	33	4.34
Temporal Cortex											
Temporal Sup	R						60	-26	20	441	5.01
Temporal Inf	R						62	-28	-16	4	4.13
Temporal Mid	R						52	-30	-14	3	4.02
Parietal Cortex											
Supramarginal	R						52	-32	28	441	5.20
	L						-64	-38	28	426	5.11
							-56	-44	28	426	4.95
Parietal Inf	L						-56	-36	46	426	3.99
Motor/Premotor Cortex											
Supp Motor Area	L						-12	-6	72	912	5.44
	R	12	-4	70	16	4.18	4	-12	78	912	4.73
		4	8	70	7	3.88					
Occipital Cortex											
Lingual	L						-14	-62	-14	18	3.93
Subcortical Areas											
Insula	R						34	-16	6	7054	7.00
Cerebellum (VI)	R						22	-74	-16	183	5.68

Cerebellum (Crus I)	R						38	-72	-34	70	4.76
							32	-66	-38	70	3.84
							38	-56	-28	4	3.94
Cerebellum (VIII)	R						30	-50	-44	6	4.07
							20	-68	-46	4	4.04
Cerebellum (IX)	L						-22	-44	-46	4	3.84
Cingulum Mid	L						-4	-8	44	912	5.27
							0	-26	46	4	3.74
Thalamus	R	18	-14	8	16	4.15					
Vermis		-34	-48	36	3.91	0					

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Table 3.8

Brain Areas Significantly Activated during KI Compared to IVI for Good and Poor Imagers

		Good Imagers					Poor Imagers				
Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]
		X	Y	z	k		x	y	z	k	
Frontal Cortex											
Frontal Inf Tri	L						-38	26	10	118	6.23
							-46	38	12	118	4.21
Frontal Inf Orb	L						-26	28	-8	116	5.93
	R						28	34	-8	8	3.99
Frontal Mid Orb	L						-24	38	-14	116	5.54
Frontal Sup Orb	L						-24	56	-2	49	4.85
	R						20	30	-12	7	4.21
Frontal Sup	L	-24	46	42	11	4.13	-18	24	56	7	3.92
							-20	64	10	3	3.73
Parietal Cortex											
Supramarginal	L						-56	-32	32	65	4.42
Parietal Inf	L	-52	44	56	5	3.97					
Motor/Premotor Cortex											
Supp Motor Area	L	-10	22	66	15	4.28					
Subcortical Areas											
Pallidum	L						-10	8	-4	125	4.96
Cingulum Mid	L						-2	-6	48	10	3.95
Caudate	R	14	8	22	40	4.48					
Hippocampus	L	-22	-26	-6	6	4.01					
Cerebellum (Crus II)	R						34	-68	-38	7	3.86
Cerebellum (VIIb)	R	28	-74	-46	6	3.93					
Cerebellum (VIII)	R	18	-68	-40	8	3.94					

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Table 3.9

Brain Areas Significantly Activated during IVI Compared to EVI for Good and Poor Imagers

		Good Imagers					Poor Imagers				
Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]
		x	Y	z	k		x	y	z	k	
Motor/Premotor Cortex											
Supp Motor Area	R	14	-6	68	4	3.79					
Occipital Cortex											
Cuneus	L						-4	-78	26	24	3.88
Subcortical Areas											
Caudate	R						16	22	-4	51	4.96
	L						-12	22	-4	3	3.90

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Table 3.10

Brain Areas Significantly Activated during EVI Compared to IVI for Good and Poor Imagers

		Good Imagers					Poor Imagers				
Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]
		x	Y	Z	k		x	y	z	k	
Parietal Cortex											
Parietal Inf	L	-38	-46	46	7	3.92					

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Table 3.11

Brain Areas Significantly Activated during EVI Compared to KI for Good and Poor Imagers

Area	L[a]/R[b]	Good Imagers					Poor Imagers				
		Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]	Local Maxima Peak Coordinates (MNI)[c]			Cluster Size[d]	T-value[e]
		X	Y	z	k		x	y	z	k	
Frontal Cortex											
Frontal Mid	R	40	32	24	7	3.98					
Temporal Cortex											
Temporal Sup	R	46	-24	60	497	4.68					
Temporal Inf	R	54	-62	-4	23	4.21					
Temporal Mid	L	-46	-62	16	66	4.13					
		-46	-70	20	66	3.94					
Parietal Cortex											
Parietal Inf	R	48	-38	54	497	5.74					
Postcentral Gyrus	L	-48	-14	46	213	4.77					
		-48	-8	58	213	4.53					
Supramarginal Gyrus	R	36	-38	42	497	6.59					
Motor/Premotor Cortex											
Precentral	L	-40	-8	56	213	4.23					
		-22	-14	64	50	4.46					
		-30	-18	58	50	3.76					
	R	46	8	32	43	4.10					
		52	12	36	43	3.92					
Paracentral Lobule	R	0	-30	68	3	3.82					
Occipital Cortex											
Occipital Mid	R						38	-70	24	9	3.98
Subcortical Areas											
Insula	R						42	20	26	11	4.06

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Table 3.12

Brain Areas Significantly Different between Good and Poor Imagers during EVI Compared to Rest

Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)			Cluster Size	T-value
		x	Y	z	K	
Motor/Premotor Cortex						
Precentral	L	-16	-14	70	55	4.04
Supp Motor Area	L	-2	-2	54	4	3.42
Occipital Cortex						
Lingual	R	20	-88	-26	3	3.43
Subcortical Areas						
Cerebellum (VIII)	R	24	-50	-40	23	3.96

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Table 3.13

Brain Areas Significantly Different between Good and Poor Imagers during IVI Compared to KI

Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)			Cluster Size	T-value
		X	Y	z	K	
Frontal Cortex						
Frontal Inf Orb	R	28	38	-8	15	3.82

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Table 3.14

Brain Areas Significantly Different between Good and Poor Imagers during KI Compared to Rest

Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)			Cluster Size	T-value
		x	Y	z	K	
Subcortical Areas						
Caudate	L	-10	8	20	22	3.68

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Table 3.15

Brain Areas Significantly Different between Good and Poor Imagers during All Imagery Conditions Compared to Rest

Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)			Cluster Size	T-value
		x	Y	z	K	
Subcortical Areas						
Caudate	L	-8	6	20	73	3.64
Cingulum Mid	R	16	-44	38	5	3.49

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Table 3.16

Brain Areas Significantly Different between Good and Poor Imagers during EVI Compared to KI

Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)			Cluster Size	T-value
		x	Y	z	K	
Frontal Cortex						
Frontal Sup Orb	R	20	36	-12	30	3.93
Frontal Mid Orb	R	32	58	-4	17	3.61
Temporal Cortex						
Heschl	R	48	-10	6	3	3.43
Parietal Cortex						
Postcentral Cortex	R	50	-18	56	8	3.62
	L	-48	-14	42	18	3.59
Motor/Premotor Cortex						
Precentral	L	-20	-16	72	271	4.24
		-22	-14	64	271	4.13
Supp Motor Area	L	-10	-6	72	271	3.94
Subcortical Areas						
Putamen	R	20	20	-2	208	4.92
	L	-28	14	2	123	3.60
		-20	10	2	123	3.57
Caudate	R	4	20	2	208	3.88
Insula	R	40	14	-8	66	4.12
Pallidum	R	20	-22	-4	26	3.55
	L	-14	2	0	123	3.69

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Table 3.17

Brain Areas Significantly Different between Poor and Good Imagers during EVI Compared to KI

Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)			Cluster Size	T-value
		x	Y	z	K	
Subcortical Areas						
Cingulum Mid	L	-6	-28	-46	37	3.41

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Table 3.18

Brain Areas Significantly Different between Poor and Good Imagers during KI Compared to EVI

Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)			Cluster Size	T-value
		x	Y	z	k	
Frontal Cortex						
Frontal Mid Orb	R	32	58	-4	17	3.61
Temporal Cortex						
Heschl	R	48	-10	6	3	3.43
Parietal Cortex						
Postcentral	R	50	-18	56	8	3.62
	L	-48	-14	42	18	3.59
Motor/Premotor Cortex						
Precentral	L	-20	-16	72	271	4.25
		-22	-14	64	271	4.13
Subcortical Areas						
Putamen	R	20	20	-2	208	4.92
	L	-28	14	2	123	3.60
		-20	10	2	123	3.57
Caudate	R	4	20	2	208	3.88
Thalamus	L	-10	-6	72	271	3.94
Insula	R	40	14	-8	66	4.12
Pallidum	R	20	-2	-4	26	3.55
	L	-14	2	0	123	3.69

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level.

Table 3.19

Brain Areas Significantly Different between Poor and Good Imagers during KI Compared to IVI

Area	L[a]/R[b]	Local Maxima Peak Coordinates (MNI)			Cluster Size	T-value
		x	Y	z	K	
Frontal Cortex						
Frontal Inf Orb	R	28	38	-8	15	3.82

Note. [a]L = left hemisphere, [b]R = right hemisphere, [c]MNI = Montreal Neurological Institute, [d]Extent threshold k = 3, [e]T-value: local maxima thresholded at the $p < 0.001$ level

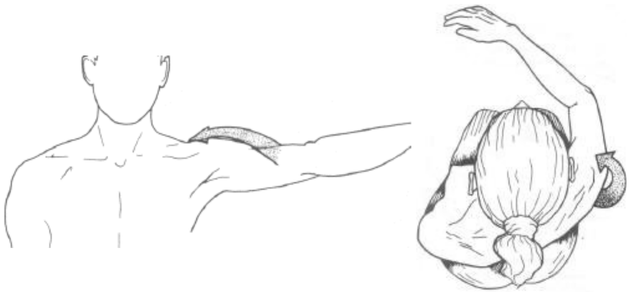


Figure 3.1
MIQ-3 arm rotation task

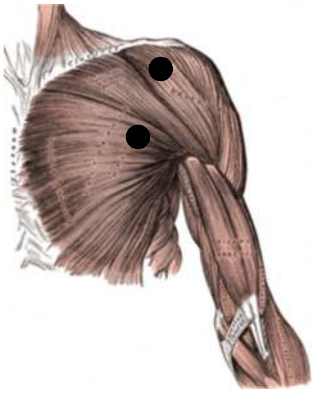


Figure 3.2

Electromyography surface sensor placement

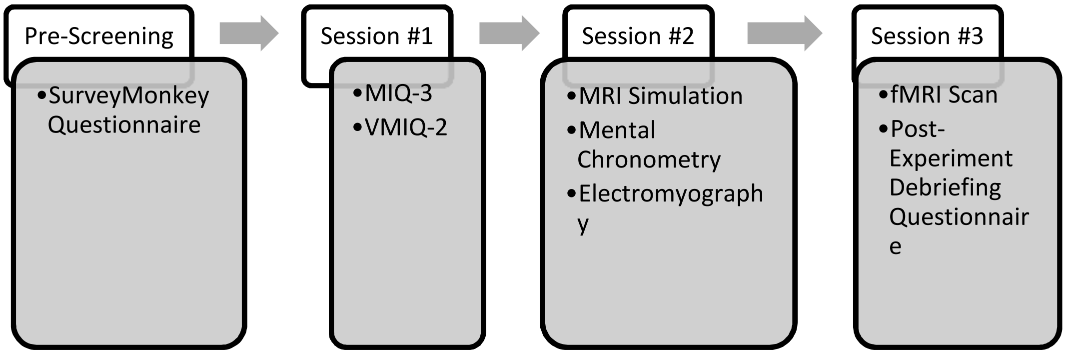


Figure 3.3
Chronological order of experiment

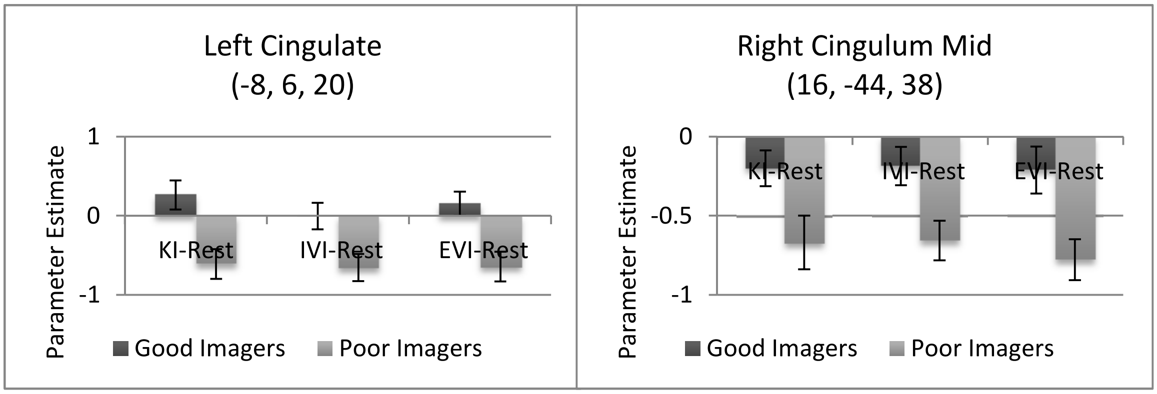


Figure 3.4
Parameter Estimates for All Imagery Conditions minus Rest for Good Compared to Poor Imagers

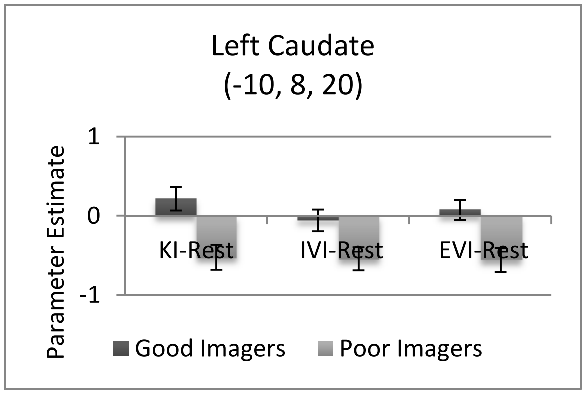


Figure 3.5

Parameter Estimates for KI minus Rest for Good Compared to Poor Imagers

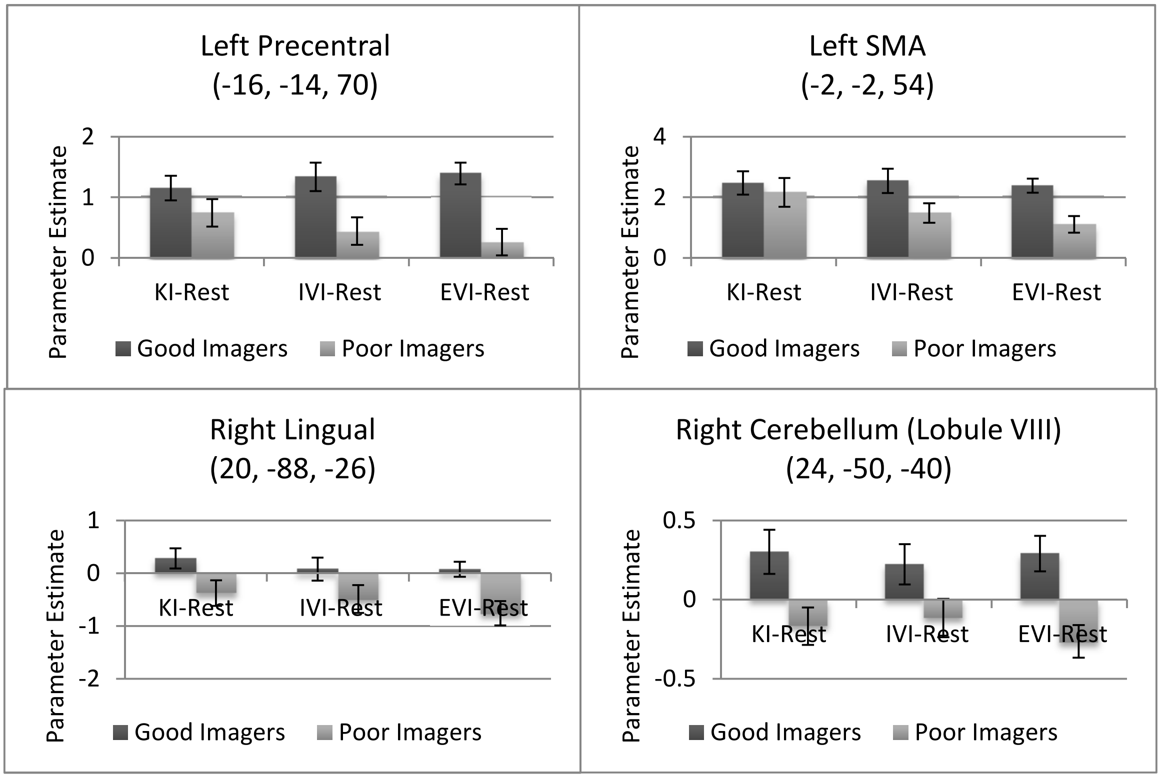


Figure 3.6

Parameter Estimates for EVI minus Rest for Good Compared to Poor Imagers

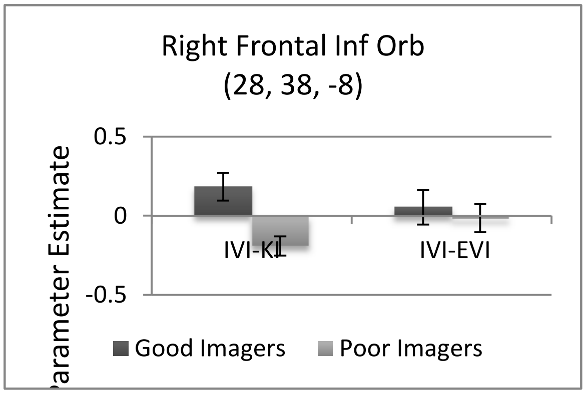
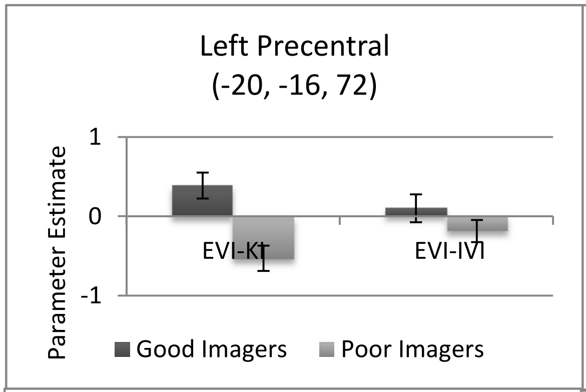
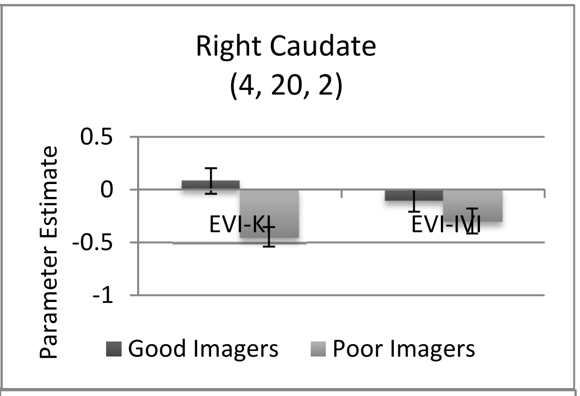
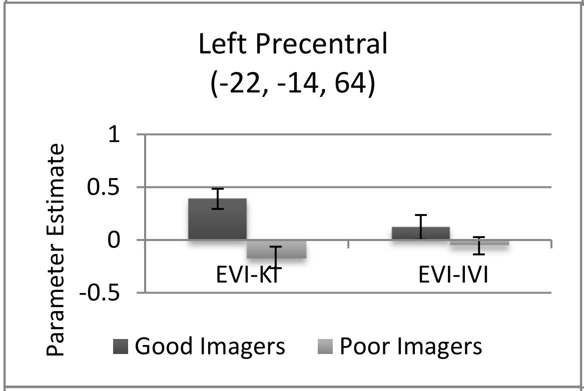
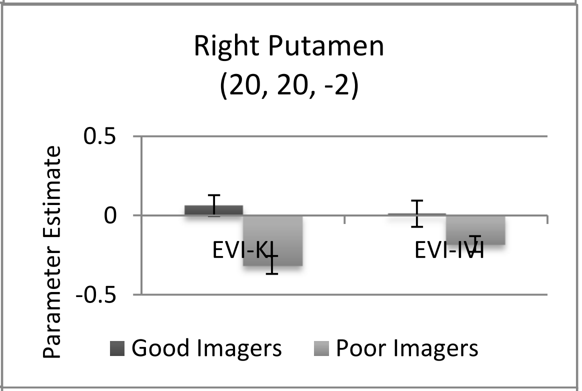


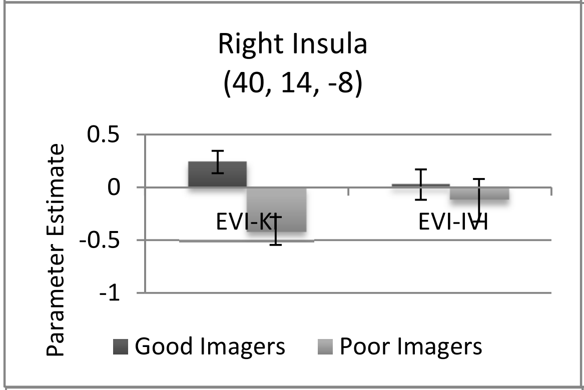
Figure 3.7
Parameter Estimates for IVI minus KI for Good Compared to Poor Imagers

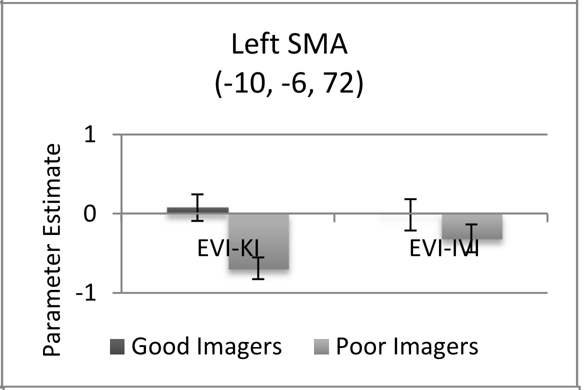

Left Precentral
(-20, -16, 72)

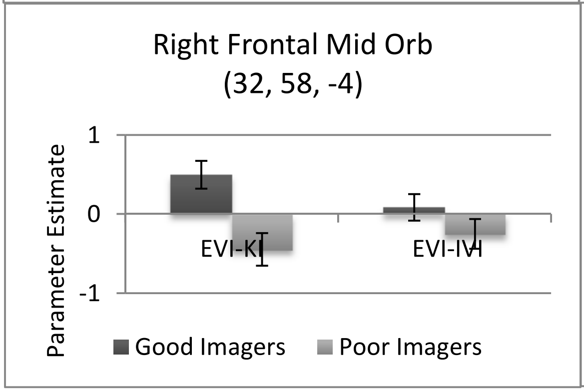

Right Caudate
(4, 20, 2)

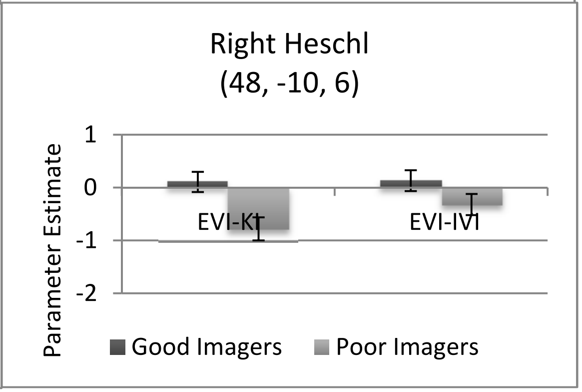

Left Precentral
(-22, -14, 64)


Right Putamen
(20, 20, -2)


Right Insula
(40, 14, -8)


Left SMA
(-10, -6, 72)


Right Frontal Mid Orb
(32, 58, -4)


Right Heschl
(48, -10, 6)

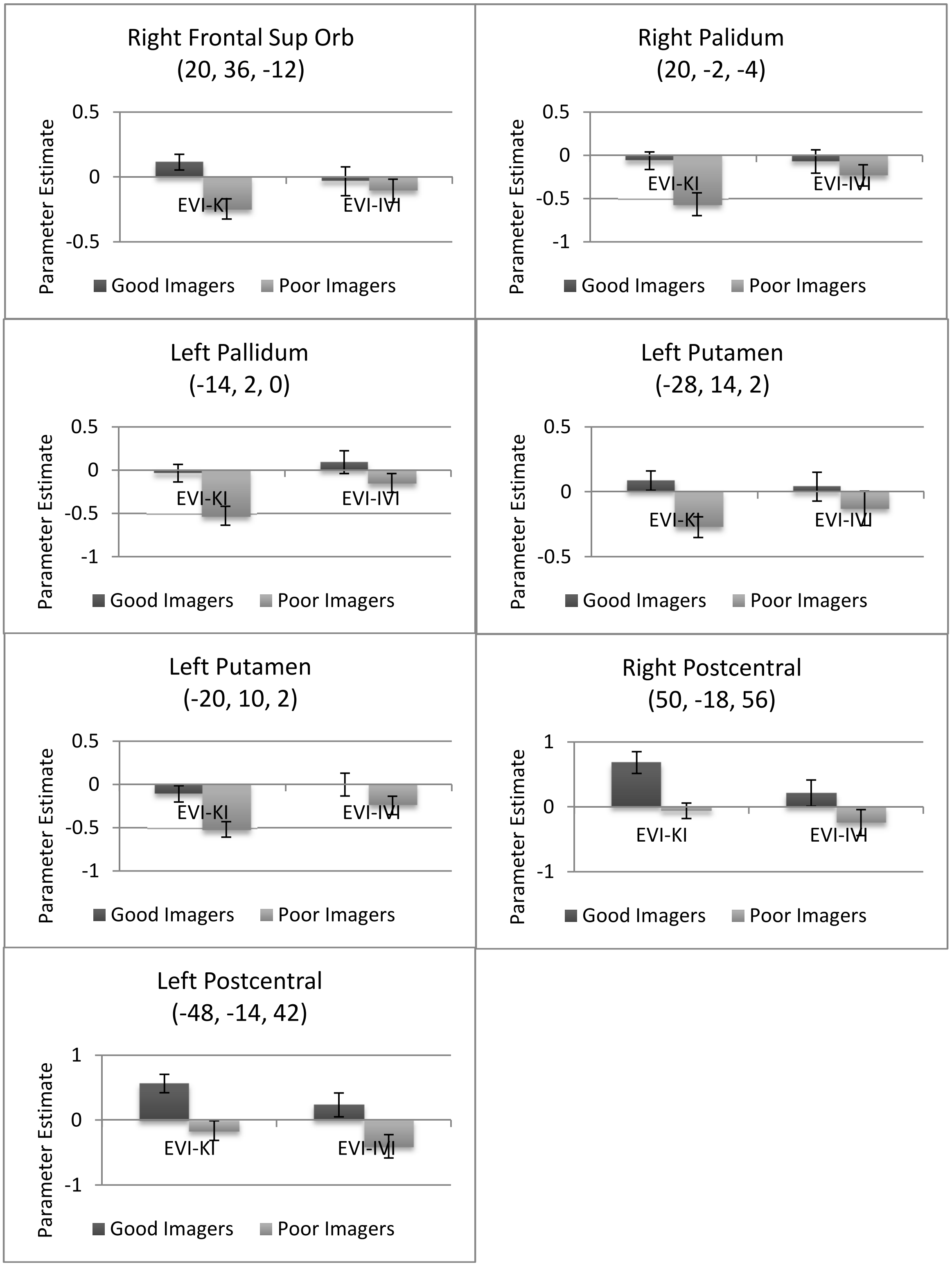


Figure 3.8

Parameter Estimates for EVI minus KI for Good Compared to Poor Imagers

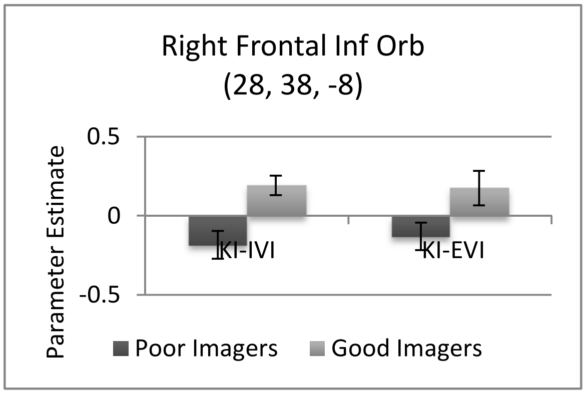
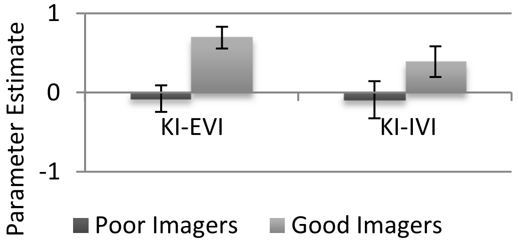


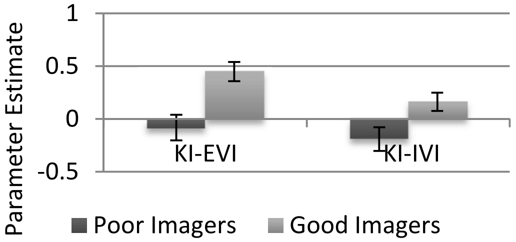
Figure 3.9

Parameter Estimates for KI minus IVI for Poor Compared to Good Imagers

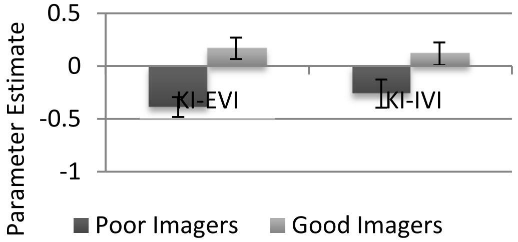
Left Thalamus
(-10, -6, 72)



Right Caudate
(4, 20, 2)

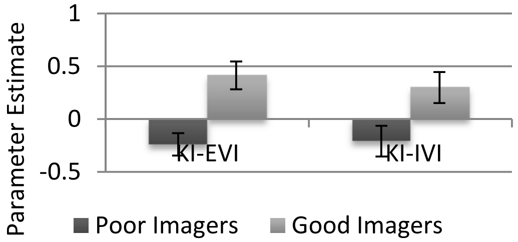


Left Precentral
(-22, -14, 64)

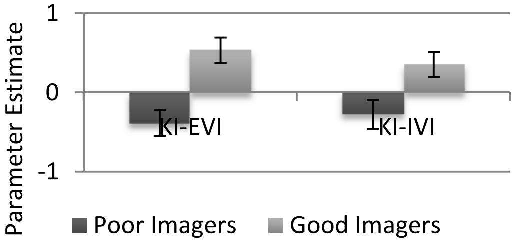


Right Putamen
(20, 20, -2)

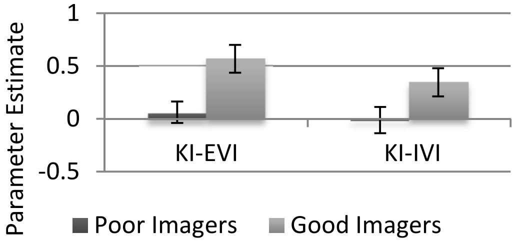
Right Insula
(40, 14, -8)



Left Precentral
(-20, -16, 72)



Right Pallidum
(20, -2. -4)



Left Pallidum
(-14, 2, 0)

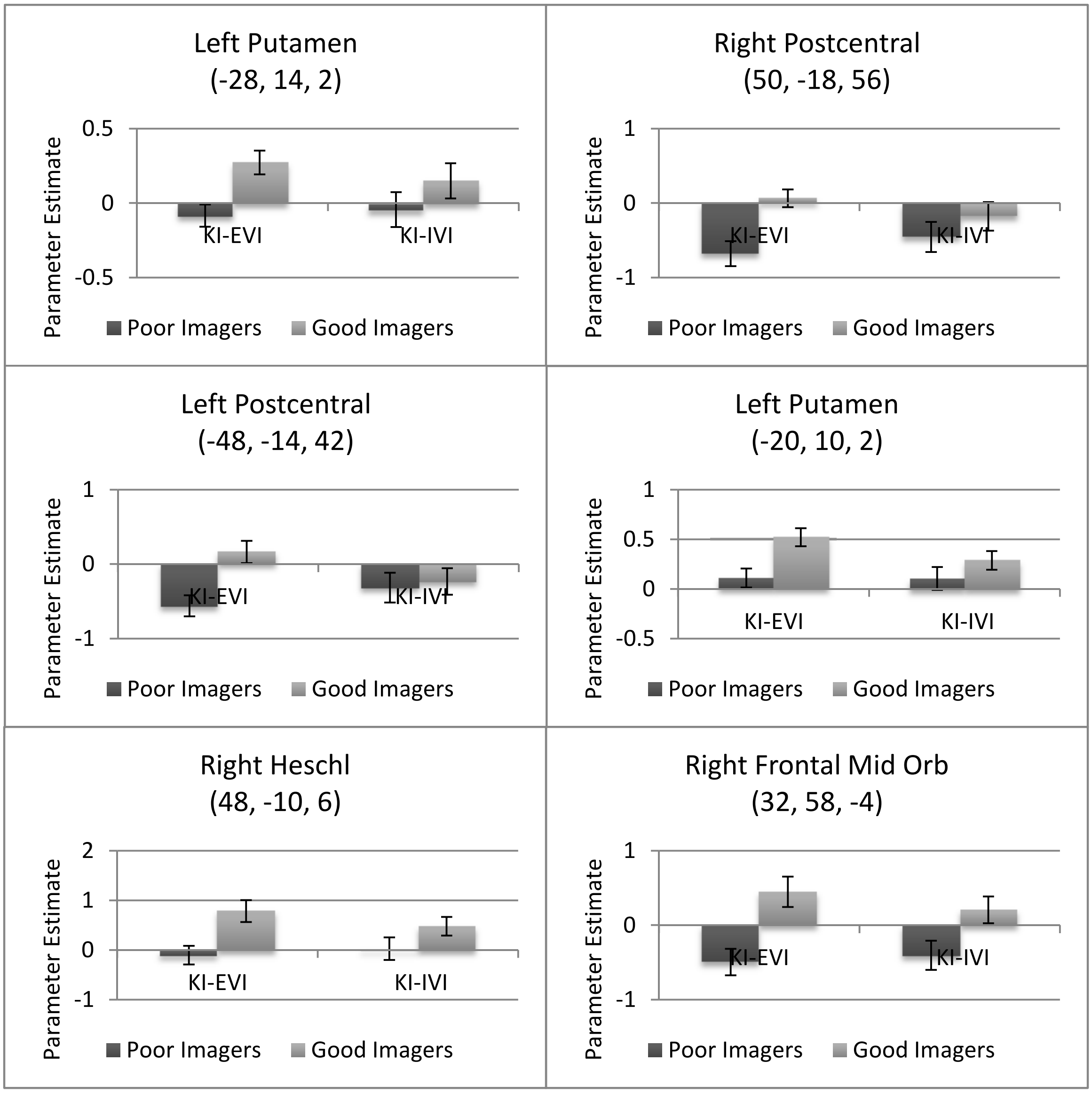


Figure 3.10

Parameter Estimates for KI minus EVI for Poor Compared to Good Imagers

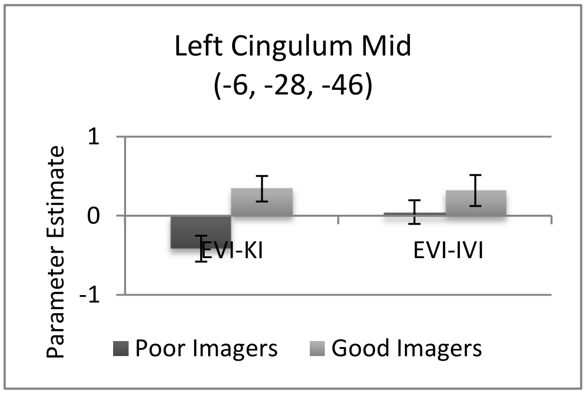


Figure 3.11
Parameter Estimates for EVI minus KI for Poor Compared to Good Imagers

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APPENDIX A – INFORMED CONSENT

"Differentiating Self-Report Imagery Ability with Functional Magnetic Resonance Imaging"

Brian D. Seiler, MS, PES, CES, ATC, Principal Investigator
Department of Physical Education and Athletic Training

Introduction and Purpose:

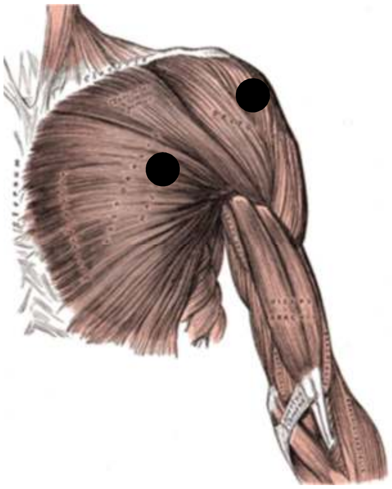
You are invited to continue your participation in a research study conducted by Brian Seiler, a doctoral candidate in the Department of Physical Education and Athletic Training at the University of South Carolina. I am completing this research study as part of the requirements for my doctoral degree in physical education. This study is funded by the College of Education and the McCausland Center for Brain Imaging, and it examines the validity of self-report imagery ability questionnaires. This form explains what you will be asked to do in the MRI portion of the study if you decide to continue your participation. Please read it carefully and feel free to ask any questions before making a decision about continuing your participation in the study.

Description of Study Procedures:

You have qualified to take part in the MRI portion of this study because of your scores on the pre-screening questionnaires you previously completed. As a selected participant, you will complete two subsequent testing sessions. For the second visit (current visit), an fMRI simulation scanning procedure will be completed. This will include the measurement of how many times that you report imagining an upper extremity movement (MIQ-3 protocol) (see Figure 1) in 30 seconds and the muscle activity (i.e., electromyography) produced by this movement. Electromyography electrodes will be places on the surface of the skin on the following muscles: pectoralis major and anterior portion of the deltoideus (See Figure 2). This session will be conducted individually and take approximately 30-45 minutes.

Figure 1. MIQ-3 protocol.

Figure 2. Electromyography (EMG) electrode placement.



You will be invited back a second time to individually complete the MIQ-3 protocol during an fMRI scan at the McCausland Center for Brain Imaging at Richland Hospital, Columbia, South Carolina. You will be positioned supine on a table with your head immobilized using foam cushions. In addition, you will be required to wear MRI-compatible headphones to indicate phases of the scan. Once positioned in the scanner, you will be required to imagine the MIQ-3 protocol according to various conditions. Instructions will be provided on a computer screen that can be clearly seen through a mirror attached to a head coil positioned in front of your face.

After reading the instructions, you will be required to close your eyes and imagine the movement using the condition identified in the directions. Each imagery period (approximately 30 seconds) will be separated by a beeping sound transmitted through MRI-compatible headphones to indicate the end of each trial. Each imagery period will be separated by a rest period of approximately 30 seconds. After competing each imagery period, you will be required to open your eyes and read the next condition on the screen. You will repeat the aforementioned procedure for a session of approximately 10 minutes.

After the fMRI scan, you will be debriefed. Here, you will be asked to rate your experience and your ability to complete the imagery tasks during the scanning session. The fMRI session will be completed individually and last approximately 60 minutes.

	Session 2	**Session 3**
Task	fMRI Simulation Scanning Procedure	fMRI Scanning Session
Location	Discovery Building (University of South Carolina, main campus)	McCausland Center for Brain Imaging, Richland Hospital, Columbia, South Carolina
Time Commitment	30 minutes	60 minutes
Payment	$20	$30

Risks of Participation:

The risks of participation in the MRI scanning procedure are minimal. Special considerations are made for the following:

- **Metal:** The MRI machine produces a constant, strong magnetic field. If you have metal implants and clips within your body they may be influenced by the magnetic field and shift in position. If you have such implants you must inform the study staff and withdraw from the study. Metal earrings and necklaces also must be removed prior to the study. If you have shrapnel, surgical implants, or other pieces of metal in your body that cannot be removed, you may not be able to participate. In many cases, if you have dental appliances in your mouth you can participate, but you should notify the primary investigator to be certain.
- **Induced Currents:** Due to changing magnetic fields during the course of operation, there is a possibility that you will experience a localized twitching sensation. This is not unexpected and should not be painful.
- **Hearing:** Functional MRI scanning produces a loud, high frequency tone that can cause hearing damage if appropriate hearing protection is not used. Adequate hearing protection will be provided and required.
- **Claustrophobia:** The functional scanning coil fits closely around your head, so if you feel anxious in confined spaces, you may not want to participate. If you decide to participate, and then at a later time decide to discontinue, just let the primary investigator know and we will stop the experiment.
- **Anxiety:** You may also experience some boredom and/or anxiety from being required to lie still for the duration of the scan.

Participant Injury:

In the unlikely event that you are injured as a result of your participation in this study, the study staff will assist you in obtaining appropriate medical treatment. However, you will be responsible for any costs associated with medical treatment.

Incidental Findings:

Some MRI scans can detect medical conditions, such as cancer, brain injury and abnormal blood vessels; however, this functional MRI is carried out purely for experimental purposes and we are not looking for brain disorders. Furthermore, we are not trained in diagnosing brain disorders; therefore, we are not qualified to off any medical opinions concerning your scan (good or bad). It is possible that we might notice something in your scan that appears unusual and/or abnormal. If this occurs, we will inform you of the finding and provide you with a copy of your scan, which you may take to a medical expert for further review and diagnosis. Being told about such a finding may cause anxiety as well as suggest the need for additional tests and financial costs. Any costs associated with a clinical follow-up opinion are your responsibility.

If you do not wish to be informed of this type of finding, you should not participate in the study.

Benefits of Participation:

Taking part in this study is not likely to benefit you personally. This project is designed to examine how the brain functions while you imagine a movement task.

Alternatives:

The alternative to this study is not to participate.

Costs:

There will be no costs to you for participating in this study other than parking or gas expenses you may incur to get to the testing sites.

Payment:

If you fully participate and complete all parts of the study you will receive a total of $50 and copy of your brain scan on a CD-ROM. This $50 will help reimburse you for your time and transportation expenses incurred as a result of the study. You will receive two payment installments. The first installment of $20 will be awarded after the completion of the fMRI simulation session at the Discovery Building located at the University of South Carolina (main campus). A second installment of $30 will be distributed at the study's conclusion at the McCausland Center for Brain Imaging (Richland Hospital, Columbia, South Carolina).

Circumstances for Dismissal from the Study

You may be dismissed from the study without your consent for various reasons, including the following:

- If you do not keep appointments for study visits or fail to complete study activities (e.g., complete forms).
- If you do not follow the instructions you are given.
- If the primary investigator believes that it is not in your best interest to continue in the study.

Confidentiality of Records

Participation in this study is voluntary. You can withdraw from the study at any time and request that data obtained through your participation be destroyed in your presence.

All information gathered will remain confidential. Throughout the study, the study staff will maintain a link to your identity. Only these individuals will be able to link your information with your name. Study records/data will be stored in locked filing cabinets and password protected computer files at the University of South Carolina. The results of the study may be published or presented at meetings, but your identity will not be revealed.

While the study staff will make every effort to protect your privacy, it cannot be absolutely guaranteed. The primary investigator and other study staff members will have access to your identifiable information. In rare cases, a research study may be evaluated by an oversight agency, such as the USC Institutional Review Board or the U.S.

Office for Human Research Protections. If this occurs, records that identify you and the consent form signed by you may be inspected so that they may evaluate whether the study is properly conducted and your rights as a participant were adequately protected.

At any time after the study, you can request that data obtained through your participation be destroyed in your presence.

Voluntary Participation

Participation in this study is voluntary. You are free not to participate or to withdraw at any time, for whatever reason, without negative consequences. In the even that you do withdraw from this study, the information you have already provided will be kept on file in a confidential manner, and you will not receive compensation. Participation is not related to regular course work and participation or withdrawal will have no impact on grades for those participants that are students. If participants are students and complete the study, a portion of their professional requirement of the department will be provided.

Contact Persons

For more information concerning this research, or if you believe you may have suffered a research related injury, you should contact the primary investigator Brian D. Seiler at 803-348-1067 or brian.d.seiler@gmail.com, faculty advisor Dr. Eva Monsma at 803-777-1386 or eavadocz@mailbox.sc.edu, or Dr. Roger Newman-Norlund at 803-777-7167 or rnorlund@mailbox.sc.edu.

If you have any questions about your rights as a research subject contact, Lisa Marie Johnson, IRB Manager, Office of Research Compliance, University of South Carolina, 901 Sumter Street, Byrnes 515, Columbia, SC 29208, Phone: (803) 777-7095 or LisaJ@mailbox.sc.edu. The Office of Research Compliance is an administrative office that supports the USC Institutional Review Board. The Institutional Review Board (IRB) consists of representatives from a variety of scientific disciplines, non-scientists, and community members for the primary purpose of protecting the rights and welfare of human subjects enrolled in research studies.

Participant and Witness Signatures:

Your signature indicates that you have read this informed consent form, and your questions have been answered by the primary investigator or a study staff representative.

____	___________________
Participant Name	Date
____	___________________
Participant Signature	Date
____	___________________
Witness Name	Date
____	___________________
Witness Signature	Date

APPENDIX B – DEMOGRAPHIC QUESTIONNAIRE

Name: __________________________________ Date: _____ / _____ / __________

Please fill in the blank or circle the appropriate answer for each of the following questions.

1. What is your ethnic group?
    - Caucasian
    - African American
    - Hispanic/Latino
    - Asian
    - American Indian
    - Pacific Islander
    - Other (*specify*) ___________________________

2. What is your highest level of education completed?
    - High School Diploma
    - Associate Degree (*specify*) _________________
    - Bachelor of Arts (BA)
    - Bachelor of Science (BS)
    - Master of Arts (MA)
    - Master of Science (MS)
    - Doctorate (PhD/EdD)

3. What is your academic major(s) (area(s) of study)?

4. Do you have a history of neurologic or psychiatric disorders?
    YES NO

5. Are you currently taking any medications that alter neurologic activity (i.e., antidepressants or ADHD)
    YES NO

6. Do you have a history of drug use or substance abuse (including alcoholism)?
    YES NO

7. Do you have a history of seizures?
    YES NO

8. Do you have a history of head trauma (including concussions) within the past five years?

YES NO

If yes, when was your last head injury?

9. Do you have normal or normal-to-corrected vision?

YES NO

10. What is your sport history? (Example: Football – 2 years; Track & Field – 4 years; Soccer – 9 years; Basketball – 1 year)

11. Do you know what mental imagery is?

YES NO

12. What is your general attitude toward mental imager?

13. Have you previously used mental imagery for performance enhancement?

YES NO

If yes, please explain.

APPENDIX C – MRI PARTICIPANT SCREENING DOCUMENT

McCausland Center for Brain Imaging
MRI Participant Screening Document

You must properly answer **ALL** the questions on this form to be considered for scanning in the MRI. If you choose not to answer any of the questions, **DO NOT SIGN** this document and inform the researcher that you wish to withdraw from the experiment.

HEIGHT _____ ft ______ in WEIGHT __________ lbs

Date of Birth _____ / _____ / ________

1) Participant History
____Yes ____ No Have you ever done metal grinding, welding or machine shop work (job, hobby or student)?
____Yes ____ No Have you ever had metal removed from your eye(s) (including metal shavings, slivers, and bullets)?
____Yes ____ No Are you claustrophobic?
____Yes ____ No Do you experience vertigo or other vestibular abnormalities?

2) Participant History
____Yes ____ No Do you have sickle cell anemia?
____Yes ____ No Do you have a medical history of cancer (your history, not family history)?
____Yes ____ No Are you pregnant or breast-feeding?
(Date of last menstrual period? _____ / _____ / ________)

3) Do you have any of the following in or on your body?
____Yes ____ No Cardiac wires or defibrillator
____Yes ____ No Venous Filter, basket or stent
____Yes ____ No Dental Implants
____Yes ____ No Eye Implant
____Yes ____ No Bullets, BBs, Pellets, Metal Fragments of any kind
____Yes ____ No Implanted device (pain pump, bone stimulator, tissue expander, IUD, etc.)

____Yes ____ No Implanted Catheter
____Yes ____ No Penile Prosthesis
____Yes ____ No Fractured bones repaired with metal
____Yes ____ No Ear Implant
____Yes ____ No Joint Replacements

4) Do you have any of the following in or on your body?
____Yes ____ No Orthodontic Braces or Permanent Retainer
____Yes ____ No Permanent Makeup (eyeliner, etc.) or Tattoo
Date of Tattoo: ______________________________________
Location of Tattoo Parlor: ________________________________

5) Do you have any of the following in or on your body?
____Yes ____ No Artificial limbs
____Yes ____ No Removable dental work
____Yes ____ No Hearing aid (must be removed before entering scan room)
____Yes ____ No Body piercing jewelry
____Yes ____ No Medication patches (including nicotine)
____Yes ____ No Underwire Bra

6) List all past surgical procedures:
____

7) List all allergies: (e.g. Latex)
____

8) Have you had an MRI before? ____Yes ____ No

The possible hazards of an MRI scan have been explained to me, and I understand that I can withdraw at this point for any reason, and that I do not have to disclose that reason to the experimenter. Your signature below indicates that you understand this screening form and attest to its accuracy. If protocols require anonymous screening forms, then your signature on the Informed Consent Form will indicate compliance with this screening instrument.

_______________________________________ __________________
Participant Signature **Date**

_______________________________________ __________________
Witness Signature **Date**

APPENDIX D – EDINBURGH HANDEDNESS QUESTIONNAIRE

Please indicate with a check (✓) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two checks (✓✓).

If you are indifferent, put one check in each column (✓ | ✓).

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

Task / Object	Left Hand	Left Hand	Right Hand	Right Hand
1. Writing				
2. Drawing				
3. Throwing				
4. Scissors				
5. Toothbrush				
6. Knife (without fork)				
7. Spoon				
8. Broom (upper hand)				
9. Striking a Match (match hand)				
10. Opening a Box (lid hand)				
Total Checks:	LH =		RH =	
Cumulative Total:	CT = LH + RH =			
Difference:	D = RH – LH =			
Result:	R = (D / CT) x 100 =			
Interpretation:	Left Handed: R < -40 Ambidextrous: -40 ≤ R ≤ +40 Right Handed: R > +40			

APPENDIX E – MOVEMENT IMAGERY QUESTIONNAIRE-3

Movement Imagery Questionnaire-3
Full Questionnaire with Instructions

Instructions

This questionnaire concerns two ways of *mentally* performing movements which are used by some people more than by others, and are more applicable to some types of movements than others. The first is attempting to form a visual image or picture of a movement in your mind. The second is attempting to feel what performing a movement is like without actually doing the movement. You are requested to do both of these mental tasks for a variety of movements in this questionnaire, and then rate how easy/difficult you found the tasks to be. The ratings that you give are not designed to assess the goodness or badness of the way you perform these mental tasks. They are attempts to discover the capacity individuals' show for performing these tasks for different movements. There are no right or wrong ratings or some ratings that are better than others.

Each of the following statements describes a particular action or movement. Read each statement carefully and then actually perform the movement as described. Only perform the movement a single time. Return to the starting position for the movement just as if you were going to perform the action a second time. Then depending on which of the following you are asked to do, either (1) form as clear and vivid a visual image as possible of the movement just performed from an internal perspective (i.e., from a 1st person perspective, as if you are actually inside yourself performing and seeing the action through your own eyes), (2) form as clear and vivid a visual image as possible of the movement just performed from an external perspective (i.e., from a 3rd person perspective, as if watching yourself on DVD), or (3) attempt to feel yourself making the movement just performed without actually doing it.

After you have completed the mental task required, rate the ease/difficulty with which you were able to do the task. Take your rating from the following scale. Be as accurate as possible and take as long as you feel necessary to arrive at the proper rating for each movement. You may choose the same rating for any number of movements "seen" or "felt" and it is not necessary to utilize the entire length of the scale.

RATING SCALES

Visual Imagery Scale

1	2	3	4	5	6	7
Very hard to see	Hard to see	Somewhat hard to see	Neutral (not easy or hard to see)	Somewhat easy to see	Easy to see	Very easy to see

Kinesthetic Imagery Scale

1	2	3	4	5	6	7
Very hard to feel	Hard to feel	Somewhat hard to feel	Neutral (not easy or hard to feel)	Somewhat easy to feel	Easy to feel	Very easy to feel

1. STARTING POSITION: Stand with your feet and legs together and your arms at your sides.

   ACTION: Raise your right knee as high as possible so that you are starting on your left leg with your right leg flexed (bent) at the knee. Now lower your right leg so you are once again standing on two feet. The action is performed **slowly**.

   MENTAL TASK: Assume the starting position. Attempt to **feel** yourself making the movement just performed without actually doing it. Now rate the ease/difficulty with which you were able to do this mental task.

   Rating: _____

2. STARTING POSITION: Stand with your feet and legs together and your arms at your sides.

   ACTION: Bend down low and then jump straight up in the air as high as possible with both arms extended above your head. Land with both feet apart and lower your arms to your sides.

   MENTAL TASK: Assume the starting position. Attempt to **see** yourself making the movement just performed from an **internal perspective**. Now rate the ease/difficulty with which you were able to do this mental task.

   Rating: _____
3. STARTING POSITION: Extend the arm of your non-dominant hand straight out to your side so that it is parallel to the ground, palm down.

   ACTION: Move your arm forward until it is directly in front of your body (still parallel to the ground). Keep your arm extended during the movement, and make the movement **slowly**.

   MENTAL TASK: Assume the starting position. Attempt to **see** yourself making the movement just performed from an **external perspective**. Now rate the ease/difficulty with which you were able to do this mental task.

   Rating: _____

4. STARTING POSITION: Stand with your feet slightly apart and your arms fully extended above your head.

   ACTION: **Slowly** bend forward at the wait and try and touch your toes with your fingertips (or, if possible, touch the floor with your fingertips or your hands). Now return to the starting position, standing erect with your arms extended above your head.

   MENTAL TASK: Assume the starting position. Attempt to **feel** yourself making the movement just performed without actually doing it. Now rate the ease/difficulty with which you were able to do this mental task.

   Rating: _____

5. STARTING POSITION: Stand with your feet and legs together and your arms at your sides.

   ACTION: Raise your right knee as high as possible so that you are starting on your left leg with your right leg flexed (bent) at the knee. Now lower your right leg so you are once again standing on two feet. The action is performed **slowly**.

   MENTAL TASK: Assume the starting position. Attempt to **see** yourself making the movement just performed from an **internal perspective**. Now rate the ease/difficulty with which you were able to do this mental task.

   Rating: _____

6. STARTING POSITION: Stand with your feet and legs together and your arms at your sides.

   ACTION: Bend down low and then jump straight up in the air as high as possible with both arms extended above your head. Land with both feet apart and lower your arms to your sides.

   MENTAL TASK: Assume the starting position. Attempt to **see** yourself making the movement just performed from an **external perspective**. Now rate the ease/difficulty with which you were able to do this mental task.

   Rating: _____

7. STARTING POSITION: Extend the arm of your non-dominant hand straight out to your side so that it is parallel to the ground, palm down.

   ACTION: Move your arm forward until it is directly in front of your body (still parallel to the ground). Keep your arm extended during the movement, and make the movement **slowly**.

   MENTAL TASK: Assume the starting position. Attempt to **feel** yourself making the movement just performed without actually doing it. Now rate the ease/difficulty with which you were able to do this mental task.

   Rating: _____

8. STARTING POSITION: Stand with your feet slightly apart and your arms fully extended.

   ACTION: **Slowly** bend forward at the waist and try to touch your toes with your fingertips (or, if possible, touch the floor with your fingertips or your hands). Now return to the starting position, standing erect with your arms extended above your head.

   MENTAL TASK: Assume the starting position. Attempt to **see** yourself making the movement just performed from an **internal perspective**. Now rate the ease/difficult with which you were able to do this mental task.

   Rating: _____

9. STARTING POSITION: Stand with your feet and legs together and your arms at your sides.

   ACTION: Raise your right knee as high as possible so that you are starting on your left leg with your right leg flexed (bent at the knee. How lower your right leg so you are once again standing on two feet. The action is performed **slowly**.

   MENTAL TASK: Assume the starting position. Attempt to **see** yourself making the movement just performed from an **external perspective**. Now rate the ease/difficulty with which you were able to do this mental task.

   Rating: _____

10. STARTING POSITION: Stand with your feet and legs together and your arms at your sides.

    ACTION: Bend down low and then jump straight up in the air as high as possible with both arms extended above your head. Land with both feet apart and lower your arms to your sides.

    MENTAL TASK: Assume the starting position. Attempt to **feel** yourself making the movement just performed without actually doing it. Now rate the ease/difficulty with which you were able to do this mental task.

    Rating: _____

11. STARTING POSITION: Extend the arm of your non-dominant hand straight out to your side so that it is parallel to the ground, palm down.

    ACTION: Move your arm forward until it is directly in front of your body (still parallel to the ground). Keep your arm extended during the movement, and make the movement **slowly**.

    MENTAL TASK: Assume the starting position. Attempt to **see** yourself making the movement just performed from an **internal perspective**. Now rate the ease/difficulty with which you were able to do this mental talk.

    Rating: _____

12. STARTING POSITION: Stand with your feet slightly apart and your arms fully extended above your head.

    ACTION: **Slowly** bend forward at the waist and try and touch your toes with your fingertips (or, if possible, touch the floor with your fingertips or your hand). Now return to the starting position, standing effect with your arms extended above your head.

    MENTAL TASK: Assume the starting position. Attempt to **see** yourself making the movement just performed from an **external perspective**. Now rate the ease/difficulty with which you were able to do this mental task.

    Rating: _____

After you have completed the mental task required, rate the ease/difficulty with which you were able to do the task in the space provided below. Take your rating from the provided scale. Be as accurate as possible and take as long as you feel necessary to arrive at the proper rating for each movement.

RATING SCALES

Visual Imagery Scale

1	2	3	4	5	6	7
Very hard to see	Hard to see	Somewhat hard to see	Neutral (not easy nor hard)	Somewhat easy to see	Easy to see	Very easy to see

Kinesthetic Imagery Scale

1	2	3	4	5	6	7
Very hard to feel	Hard to feel	Somewhat hard to feel	Neutral (not easy nor hard)	Somewhat easy to feel	Easy to feel	Very easy to feel

1) Knee lift Rating:_________

2) Jump Rating: _________

3) Arm movement Rating: _________

4) Waist Bend Rating: _________

5) Knee lift Rating: _________

6) Jump Rating: _________

7) Arm Movement Rating:_________

8) Waist Bend Rating: _________

9) Knee lift Rating: _________

10) Jump Rating: _________

11) Arm movement Rating: _________

12) Waist bend Rating: _________

APPENDIX F – VIVIDNESS OF MOVEMENT IMAGERY QUESTIONNAIRE-2

Movement imagery refers to the ability to imagine a movement. The aim of this questionnaire is to determine the vividness of your movement imagery. The items of the questionnaire are designed to bring certain images to your mind. You are asked to rate the vividness of each item by reference to the 5-point scale. After each item, circle the appropriate number in the boxes provided. The first column is for an image obtained watching yourself performing the movement from an external point of view (External Visual Imagery), and the second column is for an image obtained from an internal point of view, as if you were looking out through your own eyes whilst performing the movement (Internal Visual Imagery). The third column is for an image obtained by feeling yourself do the movement (Kinaesthetic imagery). Try to do each item separately, independently of how you may have done other items. Complete all items from an external visual perspective and then return to the beginning of the questionnaire and complete all of the items from an internal visual perspective, and finally return to the beginning of the questionnaire and complete the items while feeling the movement. The three ratings for a given item may not in all cases be the same. For all items please have your eyes CLOSED.

Think of each of the following acts that appear on the next page, and classify the images according to the degree of clearness and vividness as shown on the RATING SCALE.

RATING SCALE. The image aroused by each item might be:

Perfectly clear and as vivid (as normal vision or feel of movement) ……………RATING 1
Clear and reasonably vivid ……………RATING 2
Moderately clear and vivid ……………RATING 3
Vague and dim ……………RATING 4
No image at all, you only “know” that you are thinking of the skill ……………RATING 5

	Watching yourself performing the movement (External Visual Imagery)						Looking through your own eyes whilst performing the movement (Internal Visual Imagery)						Feeling yourself do the movement (Kinaesthetic Imagery)				
Item	Perfectly clear and vivid as normal vision	Clear and reasonably vivid	Moderately clear and vivid	Vague and dim	No image at all, you only know that you are thinking of the skill		Perfectly clear and vivid as normal vision	Clear and reasonably vivid	Moderately clear and vivid	Vague and dim	No image at all, you only know that you are thinking of the skill		Perfectly clear and vivid as normal vision	Clear and reasonably vivid	Moderately clear and vivid	Vague and dim	No image at all, you only know that you are thinking of the skill
1.Walking	5	4	3	2	1		5	4	3	2	1		5	4	3	2	1
2.Running	5	4	3	2	1		5	4	3	2	1		5	4	3	2	1
3.Kicking a stone	5	4	3	2	1		5	4	3	2	1		5	4	3	2	1
4.Bending to pick up a coin	5	4	3	2	1		5	4	3	2	1		5	4	3	2	1
5.Running up stairs	5	4	3	2	1		5	4	3	2	1		5	4	3	2	1
6.Jumping sideways	5	4	3	2	1		5	4	3	2	1		5	4	3	2	1
7.Throwing a stone into water	5	4	3	2	1		5	4	3	2	1		5	4	3	2	1
8.Kicking a ball in the air	5	4	3	2	1		5	4	3	2	1		5	4	3	2	1
9.Running downhill	5	4	3	2	1		5	4	3	2	1		5	4	3	2	1
10.Riding a bike	5	4	3	2	1		5	4	3	2	1		5	4	3	2	1
11.Swinging on a rope	5	4	3	2	1		5	4	3	2	1		5	4	3	2	1
12.Jumping off a high wall	5	4	3	2	1		5	4	3	2	1		5	4	3	2	1

APPENDIX G – DEBRIEFING QUESTIONNAIRE

Instructions: Please answer the following questions according to your mental imagery experience in the fMRI scanner.

1. Please rate to what extent you were able to focus on each imagery perspective during the scanning

Not at all									Greatly

2. Please rate to what extent you were able to focus on each imagery modality during the scanning.

Not at all									Greatly

3. Please rate to what extent you switched between the imagery perspectives.

Not at all									Greatly

4. Please rate to what extent you switched between the imagery modality.

Not at all									Greatly

5. Please rate to what extent you were able to focus on the task during the scanning?

Not at all									Greatly

APPENDIX H – MRI SIMULATION PROTOCOL

Setting-Up the Workspace

1. Place the Dell laptop next to the desktop computer on the table in the MRI simulation lab and plugin the AC adaptor into the wall electrical outlet.
2. Place the Trigno electrode box next to the Dell laptop on the table and plugin the AC adaptor into the wall electrical outlet.
3. Connect the Trigno electrode box to the Dell laptop via the USB cord.
4. Clean the MRI simulation table.

Setting-Up the Computers

<u>Dell Laptop Computer</u>

1. Turn on the Dell laptop.
2. Sign-in to the computer by using the Username and Password provided on the **orange sticky note** on the laptop.
3. Open the "EMGworks 4.0 Acquisition" software by using the icon on the desktop.
4. Once the "EMGworks 4.0 Acquisition" software is open, click on the Workflow Environment Pro icon in the middle of the screen.
5. Open the folder titled "Imagery/Brain Fun."
6. Click on the "Imagery/Brain Fun" option (icon with the wrench).

<u>Desktop Computer</u>

1. Turn on the desktop computer.
2. Sign-in to the computer by using the Username on the bottom left of the computer monitor and the Password "research."
3. Double click on the "MRI FX" icon on the desktop.
4. Once the "MRI FX" software is open, select the following sound effects in order.
    - **a.** Siemens_Ambient **(Make sure this is playing before the participant enters the MRI simulation room)**
    - b. Siemens_Localizer
    - c. Siemens_MPRAGE
    - d. Siemens_EPI
5. Set all sound effects to 50%

Beginning the Session – Informed Consent

"Hello, my name is ______________________. Thank you for coming in today to complete the second session of the study. Today we will be measuring your muscle activity via Electromyography (EMG) and taking you through an MRI simulation protocol. First, we would

like to start with having you review the informed consent document for the second part of the study. In addition, please complete the MRI Participant Screening Document.

1. Have the participant read over the informed consent document for the MRI portion of the study.
2. Review the informed consent document and ask the participant if they have any questions concerning the MRI portion of the study. The researcher will answer all questions appropriately.

"Do you have any questions after reading the informed consent document?"

"Thank you for reviewing the informed consent document. Please print, sign and date the informed consent document at the bottom of the last page. Thank you."

3. Have the participant print, sign and date the informed consent document.
4. The researcher will print, sign and date the informed consent document as the witness.

"In order to save paper, we will be providing you a copy of this informed consent document in an e-mail following this session to keep for your records."

5. Place the participant's informed consent document in the appropriate folder and inform the participant that they will receive a copy of the informed consent document in their e-mail following this session for their records.

"If there are no further questions, I will review the MRI Participant Screening Document with you."

6. Review the MRI Participant Screening Document with the participant and "de-metal" the participant.

"Now we will go through the de-metaling process. Please remove all metal from your body. This includes anything in your hair, earrings, watches, rings and bracelets, belts, anything in your pockets, or any other type of metal.

7. The researcher will complete the pantomime so that the participant will follow along.

"Ok. Now we will set you up for the MRI simulation. For this session and for the final session (session three) at Palmetto Richland Memorial Hospital we are going to have you perform the ***arm rotation task*** *that is part of one of the motor imagery ability questionnaires that you completed during the pre-screening session."*

8. The researcher will have the participant read the instructions for this movement and demonstrate the movement.

"Now we are going to apply the surface EMG electrodes to your shoulder area. We are using EMG to record the muscle activity you produce while you physically complete and imagine the arm rotation task."

Setting-Up the Participant

1. Select electrodes #1 and #2 from the Trigno electrode box.
2. Place the Trigno sensor adhesive interface strips on electrodes #1 and #2.
3. Place electrode #1 on the **superior portion of the pectoralis major muscle**, making sure that the arrow on the electrode is in line with the muscle fibers of the pectoralis major. The researcher will use the correct manual muscle test to find the muscle appropriately.
4. Turn on electrode #1 by pressing the button on the electrode, making sure that a green/yellow light appears.
5. Place electrode #2 on the **anterior portion of the deltoideus muscle**, making sure that the arrow on the sensor is in line with the muscle fibers of the deltoideus. The researcher will use the correct manual muscle test to find the muscle appropriately.
6. Turn on electrode #2 by pressing the button on the electrode, making sure that a green/yellow light appears.

Running the Session

1. Verify that you completed the **test subject** information page.
    a. Last Name: Participant's initials and study number (e.g., FL-1).
    b. Display Name: Participant's initials and study number (e.g., FL-1).
    c. Gender: Female
    d. Date of Birth: ___/___/______.
    e. Weight: ______.
    f. Height: ______.
2. Click the "Start Test" icon on the bottom right of the screen.
3. Verify the information in the **Test Run Name** box.
4. Click "OK."
5. Verify that the study design is correct.
    a. Box 1: Plot and Store.
    b. Box 2: Plot and Store x 3.
    c. Box 3: Plot and Store x 3.
    d. Box 4: Plot and Store x 3.
    e. Box 5: Plot and Store x 3.
6. Click "Run Task."

"For the first part, we are going to check to see if we have the electrode placed in the correct position to receive a good EMG recording."

7. Click "Start" to begin the first task (Box 1: Plot and Store).
8. During the first task, the researcher will check the participant for the correct Trigno electrode set-up by manually muscle testing the participant and verifying that muscle activity is occurring on the computer monitor.

"Now we will be going through the first trial. For this trial, we are asking you to physically perform the ***arm rotation task*** *with your eyes closed for 30 seconds. We will be doing this three times."*

9. Inform the participant that they will be completing the physical task first. This task will consist of the participant physically completing the arm rotation task of the MIQ-3 three times. The participant will read the instructions for the task as they are written in the MIQ-3.
    a. **Starting Position:** Extend the arm of your non-dominant hand straight out to your side so that it is parallel to the ground, palm down.
    b. **Action:** Move your arm forward until it is directly in front of your body (still parallel to the ground). Keep your arm extended during the movement and make the movement **slowly**.

"Do you have any questions about the movement?"

*"If you do not have any questions, Please start performing the **arm rotation task** when I say start. When I say stop, please stop performing the task. Also, please make sure you keep your eyes closed the entire time and do not talk."*

"Start"

10. The participant will physically complete the arm rotation task three times.

"Stop"

11. Simultaneously, instruct the participants to begin the physical task and click "Next Task" on the Dell laptop to begin the second task (Box 2: Plot and Store x 3). This task will consist of three trials. Repeat step three times. There will be a rest period between each trial. At this time, record the number of repetitions of the **arm rotation task** that the participant completes during the 30 second time period.

*"The next part of the session will take place in the MRI simulator. We are going to be completing a similar protocol to the one that you just completed, but instead you will be imagining the **arm rotation task** in various imagery conditions. During the time that you are in the MRI simulator, we ask that you remain as still as possible as if you would be in a real MRI scanner."*

*"The next part will follow a PowerPoint presentation that you will be able to view on a laptop screen through a reflection on a mirror attached to the head coil. There will be three different screens that you will see: 1) instructions, 2) blank (where you will have your eyes closed), and 3) a cross-hair that will be separated by a beeping sound. First, please read the instructions on the screen and imagine the task that is stated. Once you hear the beep, please close your eyes and imagine the task until you hear another beep. At this time, please open your eyes and remain in a resting/relaxed state looking at the cross-hair on the screen, and report how many full repetitions of the **arm rotation task** that you were able to imagine.*

"Do you have any questions?"

"If you have no further questions, we will have you get onto the scanner table. Please use the step stool and sit in the middle of the table. How, swing your legs toward the bottom of the table, placing your head in the head coil, and making sure that your shoulders are touching (or close to) the bottom of the head coil. How we will put the top part of the head coil on that has

the mirror attached so that you will be able to read the instructions on the screen while in the MIR simulation scanner."

12. Place the participant on the MRI simulation scanner table.
    a. Move the scanner table out of the MRI simulation machine.
    b. Instruct the participant to lay supine on the scanner table in a comfortable position.
    c. Place the head coil around the participant's head.
    d. Instruct the participant to remain as still as possible throughout each task.
    e. Move the scanner table into the MRI simulation machine.

"How are you doing in there?"

"Are you ready to begin?"

"Ok. The first part is a localizer so that the MRI scanner knows where your head is. This will take about 15 second. Please remain still."

13. Select the "Siemens_Localizer" sound effect for approximately 15 seconds.

"Ok. The localizer is complete. Are you still okay in there?"

"Ok. The next part will be the anatomical scan. Today we will do this for approximately 30 seconds, but the real scan will take approximately 6:30 minutes. Are you read?"

14. Select the "Siemens_MPRAGE" sound effect for approximately 30 seconds.

"The anatomical scan is complete. How are you doing in there?"

"Great! Now we will start the functional scans with the imager tasks. As a reminder, you will see a number of screens that come up in sets of three on the screen separated by a beeping sound. The first will have instructions indicating the task and an imagery condition. Once you hear the beep, please close your eyes and imagine the task in that imagery condition. When you hear the next beep, please open your eyes and attend to the cross-hair on the screen while reporting how many repetitions you were able to complete of the ***arm rotation task****. Please make sure that you remember to count each trial. Also, please remain quiet and as still as possible during each trial. Do you have any questions?"*

"If you have no additional questions, we will begin. This part of the session will take approximately 14 minutes. If at any time that you want out of the scanner because you do not feel comfortable, please let me know and I will remove you from the scanner."

15. The research will inform the participant that for the next task they will only be using imagery. Have the participant read the task instructions. This task will consist of the participant imagining, from an **external visual perspective**, the **arm rotation task** of the MIQ-3.
16. Simultaneously, instruct the participant to begin the imagery task with their eyes closed and click "Next Task" to begin the third task (Box 2: Plot and Store x 3). This task will

consist of three trials. Repeat step three times. There will be a 30 second rest period between each trial. At this time, the participant will inform the researcher the amount of full repetitions of the **arm rotation task** that they were able to complete during the 30 second trial.

17. The researcher will inform the participant that for the next task they will only be using imagery. Have the participant read the task instructions. This task will consist of the participant imagining, from a **kinesthetic perspective**, the **arm rotation task** of the MIQ-3.
18. Simultaneously, instruct the participant to begin the imagery task with their eyes closed and click "Next Task" to begin the fourth task (Box 3: Plot and Store x 3). This task will consist of three trials. Repeat step three times. There will be a 30 second rest period between each trial. At this time, the participant will inform the researcher the amount of full repetitions of the **arm rotation task** that they were able to complete during the 30 second trial.
19. The researcher will inform the participant that for the next task they will only be using imagery. Have the participant read the task instructions. This task will consist of the participant imagining, from an **internal visual perspective**, the **arm rotation task** of the MIQ-3.
20. Simultaneously, instruct the participant to begin the imagery task with their eyes close and click "Next Task" to being the fifth task (Box 4: Plot and Store x 3). This task will consist of three trials. Repeat step three times. There will be a 30 second rest period between each trial. At this time, the participant will inform the researcher the amount of full repetitions of the **arm rotation task** that they were able to complete during the 30 second trial.

"Okay. The session is now over. Please remain still as we move the scanner table out of the MRI simulation scanner."

21. Move the scanner table out of the MRI simulation scanner. Remove the head coil. Have the participant sit up and slowly step down from the scanner table using the step stool.

Concluding the Session

1. Debrief the participant of the purport for the session, and answer any additional questions that the participant may have.
2. Indicate to the participant that by completing this session that they receive a $20 compensation. Provide the participant with the $20 payment (single $20 bill) for completing the second session in a white envelope with the participant's name.
3. Have the participant print, sign and date the appropriate payment form for receiving the payment.
4. Explain the third session of the experiment, including location, directions, and parking.
5. Schedule the final session of the experiment with the participant.
6. Ask the participant if they have any remaining questions, and answer the appropriately.
7. Wipe down all surfaces with an anti-bacterial wipe.

APPENDIX I – GLOSSARY OF TERMS

Term	Abbreviation	Definition
Abduction		To draw away from the midline of the body or from an adjacent part or limb.
Apraxia		Inability to execute learned purposeful movement, despite having the desire and the physical capacity to perform the movements.
Autonomic nervous system	ANS	Part of the peripheral nervous system that acts as a control system, functioning largely below the level of consciousness, and controls visceral functions.
Basal Ganglia		Collection of nuclei associated with the control of voluntary motor movements.
Bioinformational theory		Based on the assumption that an image is a functionally organized set of propositions stored in the brain.
Blood oxygenation level dependent	BOLD	Method used in fMRI to observe difference areas of the brain, which are found to be active at a given time.
Central nervous system	CNS	Part of the nervous system consisting of the brain and spinal cord.
Cerebellum		Base of the brain that regulates motor movements/coordinates voluntary movements.
Contralateral		Relating to or denoting the side of the body opposite to that on which a particular structure or condition occurs.
Controllability		Ease and accuracy that the image content can be manipulated and transformed.
Cortical		Involving or resulting from the action or condition of the cerebral cortex.
Deconvolution		Algorithm-based process used to reverse the effects of convolution (mathematical operation on two functions, *f* and *g*, producing a third function) on recorded data.
Echo-time	TE	Time interval between an excitation pulse and data acquisition (defined as the collection of data from the center of *k*-space), usually expressed in milliseconds

Edinburgh handedness inventory	EHI	Measurement scale used to assess the dominance of a person's right or left hand in everyday activities.
Electroencephalography	EEG	Recording of the difference in electrical activity between various points of the cortex using electrodes placed at specific point on the scalp.
Electromyography	EMG	Technique for evaluating and recording the electrical activity produced by skeletal muscles.
External visual imagery	EVI	Where the imager is watching him or herself performing the action from an observer's position; as if watching him or herself on television.
F-wave		Second of two voltage changes observed after electrical stimulation is applied to the skin surface.
Fitts' law		Model of human movement predicting that the time required to rapidly move to a target area is a function of the distance to the target and the size of the target.
Functional equivalence theory		Hypothesizes that mental images are internal representations that work in the same way as the actual perception of physical objects.
Functional magnetic resonance imaging	fMRI	Procedure using the different magnetic properties of oxygenated (arterial) and deoxygenated (venous) blood to identify blood flow.
Global imagery score		Method to select good and poor imagers using the formula: (ANS score + imagery questionnaire score + auto-estimation score) – (mental chronometry score).
Gradient-echo		Signal that is detected in a nuclear magnetic resonance spectrometer produced by varying the external magnetic field following the application of a single radio-frequency pulse.
Gradient-echo echo-planar imaging		One of the two primary types of pulse sequences used in MRI; it uses gradients to generate the MR signal changes that are measured at data acquisition.

Gyrus		Ridge on the cerebral cortex.
Hemodynamic response		Relating to or functioning in the mechanics of blood circulation in response to stimuli.
Horizontal flexion		Moving the arm forward in a horizontal plane.
Internal visual imagery	IVI	Where the imager is looking out through his or her own eyes while performing an action.
Interpolation		Method of constructing new data points within the range of a discrete set of known data points.
Ipsilateral		Belonging to or occurring on the same side of the body.
Kinesthetic imagery	KI	Where the imager feels him or herself performing a movement, specifically detecting bodily position and movement of the muscles, tendons, and joints.
Magnetic resonance imaging	MRI	Imaging technique that uses radio waves to excite atoms in the brain, which are detected by a large magnet that surrounds the individual.
Mental chronometry	MC	Use of response time in perceptual-motor tasks to infer the content, duration, and temporal sequencing of cognitive operations.
Mental rotation		Ability to rotate mental representations of objects.
Motor evoked potential	MEP	Electrical potential recorded from the nervous system following presentation of a stimulus.
Motor imagery	MI	Mental process by which an individual rehearses or simulates a given action.
Motor imagery index	MII	A combination of psychometric tests, qualitative procedures, chronometric methods, and psychophysiological techniques to measure MI quality.
Movement imagery questionnaire-3	MIQ-3	12-item questionnaire to assess individual’s ability to image four movements using internal visual imagery, external visual imagery, and kinesthetic imagery.

Neural substrates		Indicates a part of the nervous or brain system that underlies a specific behavior or psychological state.
Parietal lobe		One of the four major lobes of the cerebral cortex of the brain integrating sensory information among various modalities.
Pitch		Rotation of a rigid body about its transverse (side-to-side) axis.
Positron emission tomography	PET	Nuclear medicine, functional imaging technique that produces a three-dimensional image of functional processes in the body.
Precuneus		Part of the superior parietal lobule involved with episodic memory, visuospatial abilities, and motor activity coordination strategies.
Prefrontal cortex	PFC	Brain region that plays a role in the regulation of complex cognitive, emotional, and behavioral functioning.
Premotor cortex	PMC	Complex area of interconnected frontal lobe areas that contributes to motor function.
Primary motor cortex	M1	Brain region located in the posterior portion of the frontal lobe responsible for planning and executing movements.
Psychoneuromuscular theory		Proposes that imagery facilitates the learning of motor skills because of the nature of the neuromuscular activity patterns activated during imaging.
Putamen		Round structure located at the base of the forebrain that regulates movements and influences various types of learning.
Region of interest	ROI	Selected subset of samples within a dataset identified for a particular purpose.
Regional cerebral blood flow	rCBF	Blood supply in the brain at a given time.
Repetition time	TR	Time interval between successive excitation pulses, usually expressed in seconds.
Roll		Rotation of a rigid body about its longitudinal (front/back) axis.
Root mean square EMG	EMGrms	Method used to produce waveforms that are more easily analyzable than raw EMG.

Signal-to-noise ratio		Relative strength of the signal compared with other sources of variability in the data.
Simulation theory		Predicts a similarity, in neural terms, between the state where an action is simulated and the state of execution of that action.
Single photon emission computerized tomography	SPECT	Nuclear medicine tomographic imaging technique using gamma rays to provide true three-dimensional information.
Somatosensory cortex		Outermost layer of the brain that receives and interprets most of the human sense of touch.
Somatosensory evoked potential	SEP	Electrical potential recorded by stimulating peripheral nerves.
Spatial resolution		Ability of an imaging device to distinguish the smallest discernible detail of an image.
Statistical parametric mapping	SPM	Software package designed for the analysis of brain imaging data sequences.
Subcortical		Of, relating to, involving, or being part of the nerve centers below the cerebral cortex.
Sulcus		Depression or fissure in the surface of the brain.
Supplementary motor area	SMA	Part of the cerebral cortex that contributes to the control of movement.
Symbolic learning theory		Suggests that imagery may function as a coding system to help people understand and acquire movement patterns.
T1-weighted		Images that provide information about the relative T1 values of tissue; also known as T1 images.
T2*-weighted		Images that provide information about the relative T2* values of tissue; T2*-weighted images are commonly used for BOLD-contrast fMRI.
Temporal resolution		The precision of a measurement with respect to time.
Tesla	T	Unit of measurement quantifying the strength of a magnetic field.
Thalamus		Structure in the brain responsible for relaying sensation, spatial sense and motor signals to the cerebral cortex.

Transcranial magnetic stimulation	TMS	Method that uses a magnetic field to stimulate specific cortical neurons during imagery to determine the stimulated area’s contribution to imagery.
Vividness		Self-report of how clear and real an image is; related to the level of interest, meaningfulness, and affect associated with the image generated.
Vividness of motor imagery questionnaire-2	VMIQ-2	36-item questionnaire to assess individual ability to vividly image 12 movements using internal visual imagery, external visual imagery, and kinesthetic imagery.
Voxel		Represents a value on a regular grid in three-dimensional space.
Yaw		Rotation of a rigid body about its vertical axis.