THE EFFECT OF ACTION OBSERVATION AND MOTOR IMAGERY ON CORTICOSPINAL EXCITABILITY DURING A MOTOR-RELATED TASK IN HEALTHY ADULTS

By

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List of Abbreviations Used

PP - Physical practice

MI - Motor imagery

AO - Action observation

AO+MI - Simultaneous action observation and motor imagery

MEPs - Motor-evoked potentials

TMS - Transcranial magnetic stimulation

SMA - Supplementary motor area

Abstract

Although action observation and motor imagery have typically been viewed as independent techniques for motor learning, research has found increased learning outcomes when action observation and motor imagery are used simultaneously. While behavioural studies have shown the combined use of action observation and motor imagery results in greater learning outcomes, the link between neurophysiological processes behind the enhanced performance outcomes previous studies have found is largely unknown. A scoping review with an overarching objective of investigating the effect of AO, MI and AO+MI on corticospinal excitability during a motor-related task was performed, with a secondary objective of identifying methodological factors (e.g. task type, session length) that influence increased corticospinal excitability. Findings revealed AO+MI did not result in significantly increased corticospinal excitability compared to AO or MI alone. Increased performance outcomes may be attributed to increased activity during AO+MI of areas outside of the primary motor cortex.

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Lastly, I would like to dedicate this thesis to my dog Koppy, thanks for being a very good boy.

Chapter 1: Introduction

1.1 Motor Learning

1.1.1 Physical execution

Motor learning, the improvement and acquisition of a motor skill, is achieved through repeated practice of a skilled movement. Through repeated exposure, sensory information related to the execution and outcome of the movement is obtained, allowing for the detection and subsequent correction of errors in order to refine the movements. Regardless of the skill being executed, a necessary precursor to motor learning is an increase in the excitability of the neurons that comprise the neural network underlying the skill being performed. Alongside the error detection/correction mechanism, repetition of the movement drives modification of the neural network(s) specific to the movement being executed through synaptic plasticity, which ultimately results in long-term changes that results in improved movement execution (Newell, 1991). Although the amount of exposure needed to gain expertise of a skill varies based on the complexity of the movement, through repeated exposure and feedback, movements become more refined and automatic as the individual moves closer to gaining expertise of the skill (Fitts & Posner, 1967).

1.2 Alternative Motor Learning Modalities

While physical practice (PP) is the gold standard for motor skill acquisition, it has been well-documented that motor learning can occur independent of physical execution (DiRenzo et al., 2016; Eaves et al., 2016; Jeannerod, 1995). Alternative motor learning modalities have been successfully applied in a variety of disciplines, such as rehabilitation, high performance sports, and vocational training (Afrouzeh et al., 2015; DiRenzo et al., 2016; Eaves et al., 2016) . Two prominent alternatives to PP are motor imagery (MI), the imagined performance of a movement, and action observation (AO), the observation of a movement. Similar to PP, MI and AO have been shown to facilitate changes in brain activity which in-turn are responsible for driving the neural processes necessary for learning to occur (Hetu et al., 2013).

1.2.1 Motor Imagery

MI involves an individual imagining themselves performing a movement without physically executing the movement. Previous research has demonstrated that mental rehearsal of a movement, prior to physical execution, results in increased performance outcomes compared to the absence of mental training prior to physical execution (Collins & Carson, 2017; Holmes & Collins, 2001). Although traditionally preformed as a precursor to or in adjunct with PP (Schuster et al., 2011), MI has more recently been applied independently in cases when motor learning or re-learning cannot be performed (Sharma et al., 2006). There is a paramount of evidence supporting MI as an alternative learning modality, albeit not as effective to PP, in areas where PP is not an option such as rehabilitation post brain injury (DiRenzo et al., 2016), with findings showing increased motor learning outcomes of simple and complex movements (Jackson et al., 2003; Malouin et al., 2013; Smith et al., 2008). Previous research has shown that MI has similarities to PP as it pertains to brain activity (Burianova et al., 2013; Hetu, et al., 2013). Specifically, previous work has shown increased corticospinal excitability during MI relative to rest, thus fostering an environment for learning to occur (Helm et al., 2015; Stinear & Byblow, 2004). These findings provide neurophysiological evidence that MI is an effective learning modality through the simulation of a motor movement similar to PP, however this is achieved internally and is driven by a top-down process (cognitively driven via internal simulation of movement).

1.2.2 Action Observation

While AO, the observation of a movement, has been shown to produce learning when observation is passive in nature (with no underlying intent to learn the observed movement), previous studies have shown that deliberate AO (observing a movement with the intent to learn) has been shown to result in faster and more accurate performance of the observed skill during subsequent physical execution (Brass et al., 2000; Eaves et al., 2016; Eaves et al., 2014). Previous work has shown the observation of a movement activates specific motor regions in the brain consistent with the observed action. Additionally, similar to PP, an increase in corticospinal excitability is seen in the corresponding brain areas to the action being observed (i.e. hand and arm representations during a basketball free-throw; Hari et al.,1998; Spunt et al., 2011; Strafella & Paus, 2000). Thus, learning via AO is hypothesized to be possible due to AO being a bottom-up process (perceptually driven through external stimuli) of motor simulation, as such, prior studies have found AO to be more beneficial in the earlier stages of learning, prior to the formation of a motor program (McNeill et al., 2019).

1.2.3 Action Observation + Motor Imagery

While AO and MI have been found to facilitate a neuronal response in the brain that is consistent with learning during PP, recently studies have investigated the effect of AO and MI applied simultaneously; known as AO+MI, it requires participants to engage in both MI and AO at the same time (e.g. imagining a finger tapping movement while watching another person perform a finger tapping movement), with studies showing enhanced learning outcomes of both simple and complex movements (Eaves et al., 2016; Romano-Smith et al., 2018; Vogt et al., 2013). It is hypothesized that through congruent AO+MI, where the action being observed and the movement being imagined are equivalent (i.e. observing the clasping of a hand while the individual simultaneously imagines clasping their hand), the motor simulation is able to map onto the observer's own body schema (observed hand mapped to individual's hand), and this ease of mapping is likely reflected in the greater activation of cortical regions during AO+MI. For instance, when an individual is observing a golf putt from the first-person perspective while imagining themselves performing a golf putt in synchrony, there is an increased sense of ownership of the image, allowing for easier mapping onto the limb (Atschuler et al.,1999; Kand et al., 2011). Neurophysiological studies have shown both MI and AO elicit a response from the motor system similar to physical execution, albeit at a reduced magnitude (Burianová et al., 2013; Hétu et al., 2013; Kraeutner et al., 2014). Although behavioural studies have more so consistently shown the combined use of AO and MI results in greater learning outcomes, the link between neurophysiological processes behind the enhanced performance outcomes previous studies have found is largely unknown due to the lack of learning studies including behavioural and neurophysiological conditions for AO, MI and AO+MI (Eaves et al., 2016; Romano-Smith et al., 2018). If AO+MI results in greater performance outcomes, the underlying neural activity during AO+MI that is responsible for the increased performance should also result in greater activation of the brain compared to either modality alone. Under this assumption, AO+MI should have a cumulative effect on brain activity. However, as mentioned above, previous research presenting neurophysiological findings (Eaves et al., 2016; Fadiga et al., 1999; Meers et al., 2020;

Wright et al., 2014), suggest that AO or MI independently may be driving the effect seen during AO+MI.

1.3 Present Study

In order to investigate the changes in corticospinal excitability via motor evoked potentials (MEPs), with the amplitude of the MEP being indicative of the degree of corticospinal excitability, with increased excitability representative of an environment conducive to motor learning, literature related to the effect of training modality (AO+MI, AO, MI) was synthesized via a scoping review. The goal of the scoping review is to investigate the effect of AO, MI and AO+MI on corticospinal excitability during a motor-related task, with a secondary objective of identifying methodological factors (e.g. task type, task length) that influence increased corticospinal excitability.

Chapter 2: Background and Rationale

2.1 Motor Simulation Theory

The premise behind MI and AO as alternate modalities for learning stems from motor simulation theory: if motor-related cognitive states, such as MI and AO, are similar to PP they should elicit, at least in part, a neural response utilizing motor system processes seen during execution (Jeannerod 2001, 2004). Based on motor simulation theory, motor systems can be elicited without overt movement. Therefore, through the use of MI or AO, motor systems involved in the execution of movement can be activated, allowing for anticipation of errors and outcomes (Jeannerod, 2004). Therefore, the main elements of motor simulation include movement representation on a continuum from simulation to execution, with motor simulation containing the majority of aspects included in execution such as the goal of the movement, the motor plan, and movement outcomes. It is believed that motor simulation relies on the same neural mechanisms as motor execution, however execution of the movement is inhibited (Moran, 2017).

2.2 Motor Imagery: An Internal Representation of Movement

Evidence of MI as an internal representation of movement originates from a wide variety of paradigms, including mental chronometry, mental rotation, neurophysiology and imaging studies (Cerettelli, 2000; Cooper & Shepard, 1975; Eaves et al., 2016). Similar to PP, MI has been shown to produce learning, resulting in increased performance outcomes with the underlying driver of learning being activation of brain regions similar to activity seen during PP (Hetu, et al., 2013; Burianova et al., 2013). Findings from these areas of research have been prominent in the development of the theory that learning through MI is possible due to MI being an internally guided representation of movement that is created through a *conscious top-down cognitive-drive*n process (Jeannerod & Frak, 1999).

2.3 Evidence of Motor Representation in Imagery

2.3.1 Mental chronometry

Initial evidence supporting the notion that MI, at least in some capacity, facilitates learning by relying on an internally generated movement representation that is similar to PP, comes from mental chronometry studies of both simple and complex motor tasks. Decety and colleagues (1989) investigated the difference in the perceived time to walk a predetermined distance using MI and the actual time taken to physically walk the same distance. Findings showed that perceived time estimated via MI and actual time via walking were relatively equivalent. These finding held true when the added variable of weight bearing load was included, proportionately extending the time taken for both the imagined and physical conditions. Studies that examined more complex motor tasks such as badminton, drawing, and golf putting extended these findings of chronometry equivalence by providing evidence that task complexity does not impact timing results for task completion via MI or physical execution (Gulliot et al.2002; Munzert et al., 2002; Munzert et al., 2008), suggesting MI and physical execution are overlapping the same temporal brain regions involved in motor representation of imagined and physical movements.

2.3.2 Mental rotation

Further evidence supporting the theory that MI creates a top-down internal representation of movement comes from mental rotation studies where two objects are presented, one in the correct orientation and the other in an incorrect orientation (Shepard

& Metzler, 1971). The individual must mentally rotate the incorrectly oriented object in order to report if the two objects are structurally the same or different (Figure 1). Motor constraints placed on these mental rotation tasks, such as increased number of rotations needed to match the two objects, has been shown to have an effect on reaction time, resulting in slower reaction times during MI (Wexler et al., 1998). These findings parallel conditions in which participants physically rotate the object, with more complex rotations taking longer to complete.

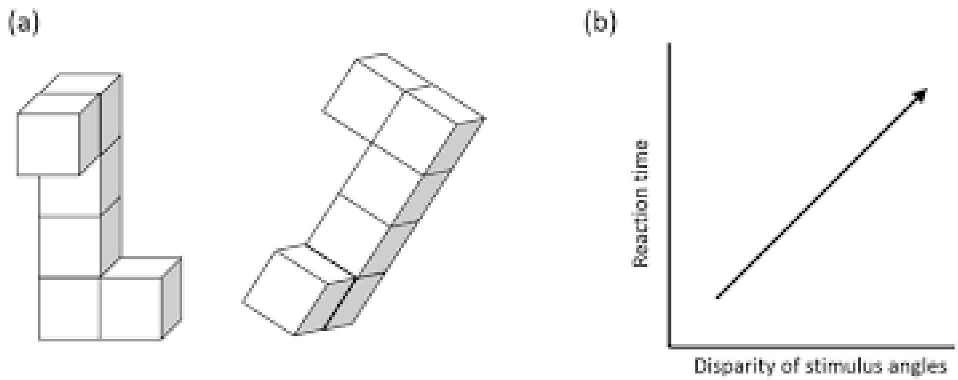


Figure 1. (a) Mental rotation task, (b) reaction time results with increased rotational disparity.

While visual perception certainly plays a role in mental rotation, cognitive motor mechanisms have also been found to be involved in the rotation of objects and body parts (Petit et al., 2003). There have been a number of studies investigating corticospinal excitability via transcranial magnetic stimulation (TMS), such as a study by Ganis and colleagues (2000), that found corticospinal excitability to be increased in areas that are consistent with the image being rotated (greater activation in the hand knob region when mentally rotating a hand versus a foot). These findings mirror those of studies in which participants physically rotated their limb, having greater activation of the corresponding neural region, leading to the notion that an internal motor representation is activated during

MI in order to successfully complete the task (Cohen et al., 1996). The parallel findings between MI and physical execution of object rotation tasks, task completion time and increased corticospinal excitability in corresponding neural regions, postulates that object rotation via MI elicits corresponding processes in the brain that are present during physical execution of the rotation task.

2.3.3 Physiological Findings

While the aforementioned studies illustrate the cognitive role of MI in forming internal motor representations without physical execution, studies investigating whether physiological processes seen during physical execution are also present during MI have provided substantial evidence that motor representations are a part of a larger cognitive network that can be simulated without physically executing a movement (Jeanrod, 2001, 2006, MST 2017). For example, studies recording peripheral nervous system activity, such as cardiac and respiratory rate during a motor task, found comparable activity between physiological measures when the task was performed physically and via imagery. These findings can be illustrated via work from Decety et al (1991), that found cardiac and respiratory activity increased during MI at a proportional rate to physical execution of leg presses. However, heart rate and respiratory activity peaked earlier during MI than actual execution. These findings suggest that MI may elicit similar autonomic processes that are seen during the preparatory and initial stages of physical execution (Decety et al., 1991; Decety et al., 1989). Due to the autonomic nature of physiological activity, eliciting a similar physiological response to execution at the peripheral level, MI must be stimulating motor regions that are consistent with physical execution.

2.3.4 Neural components of imagery

While behavioral and physiological measures have provided sufficient evidence supporting the theory that MI is an internal cognitive-driven representation of movement, neuroimaging studies offers deeper insight into the equivalences as well as the differences between imagery and physical execution. Hardwick et al. 2018 conducted a meta-analysis investigating neuroimaging studies that identified neural regions distinct to MI, and regions common during MI and execution. MI was found to primarily recruit the bilateral premotor rostral inferior in the middle superior parietal, basal ganglia, and cerebellar regions including a left lateralized recruitment of the dorsolateral prefrontal cortex (Figure 2).

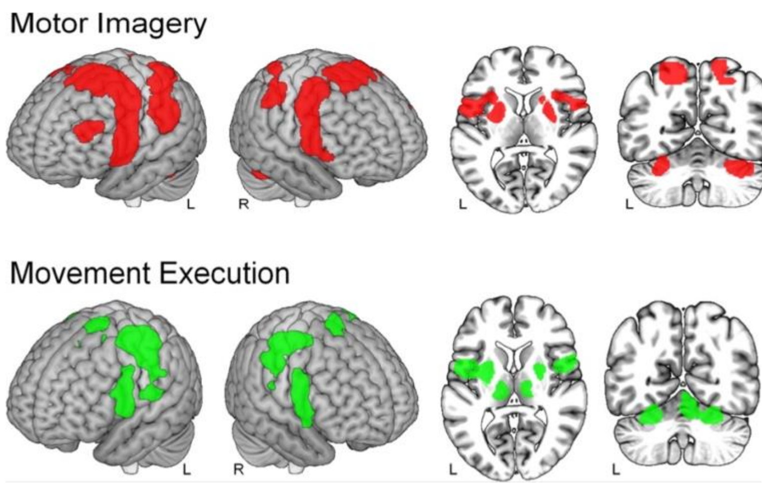


Figure 2. Activation patterns during MI and movement execution determined via conjunction analysis of 303 neuroimaging studies. Adapted from Hardwick et al. (2018).

Furthermore, conjunction analyses by Hardwick and colleagues found both MI and physical execution included a network involving bilateral cortical sensory motor and premotor clusters with a smaller sub-cortical cluster found in the putamen and the cerebellum. Additionally, the bilateral supplementary motor area (SMA) and pre-SMA as well as clusters in the right dorsal premotor cortex and ventral premotor cortex were found to be active in both imagery and execution (Figure 3). These finding indicate that while MI has distinct areas of activation there is considerable overlap between imagery and execution in motor regions providing neurological evidence that MI simulates a motor representation utilizing the same pathways as execution.

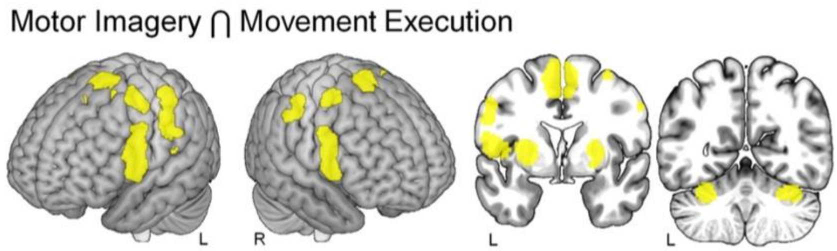


Figure 3: Overlapping brain regions (bilateral inferior parietal lobe, left inferior frontal gyrus, supplementary motor area, and bilateral cerebellum) recruited during MI and execution, determined via conjunction analyses of 303 neuroimaging studies, relative to PP controls. Adapted from Hardwick et al., (2018).

2.3.5 Neurophysiological Finding

For MI to be effective for learning, conditions similar to that observed during PP should result from MI-based training, including increased excitability of corticospinal neurons that is a precursor for plasticity. As mentioned above, TMS, a non-invasive form of brain stimulation, is commonly used to assess corticospinal excitability via MEPs. Briefly, TMS can be applied to neurons in the primary motor cortex, eliciting a response (i.e. the MEP) in the muscle corresponding to the region targeted in the cortex. The amplitude of the MEPs obtained are indicative of the level of corticospinal excitability. It is generally accepted that increased excitability of cortical neurons comprising the network underlying task performance facilitates synaptic plasticity, a process which ultimately underlies long-term potentiation and lasting structural and functional changes in the brain that manifest at the behavioural level as improved task performance (i.e. learning; Avanzino et al., 2015). As such, the use of TMS to assess corticospinal excitability (via MEP amplitude) is a means to probe the underlying processes occurring at a neuronal level that result in learning and which is quantified via behavioural outcomes. In other words, corticospinal excitability (obtained via TMS) is not a measure of learning per se, rather it is a means to examine changes in the brain that produce an environment in which learning occurs. Previous research has found that similar to PP, MEP amplitude during MI is increased compared to MEP amplitude obtained at rest, providing evidence that MI drives underlying neurophysiological changes that are present during PP and are responsible for facilitating changes in the brain necessary for learning to occur (Hashimoto & Rothwell, 1999; Helm et al., 2015; Stinear & Byblow, 2004). Increased corticospinal excitability seen during MI, along with the above-mentioned neuroimaging findings (Hardwick et al., 2019), provides a neural context for the effectiveness of MI as a motor learning modality due to MI facilitating changes in the brain that drive learning and in-turn result in enhanced behavioural outcomes (Lee et al., 2020).

2.4 Action Observation: An External Representation of Movement

Similar to MI, AO facilitates learning of both simple and complex movements in conjunction to and independent of PP (Eaves et al., 2016). In contrast to MI, AO is the *externally guided* simulation of movement, consisting of a bottom-up process that is typically unconscious and perception-driven in nature (Shepard, 1989; Heyes et al., 2001). While AO can occur naturally in a passive environment (Shepard 1991), when implemented into a learning paradigm the observer is instructed to deliberately observe a movement being performed and to focus on the kinematics of the person's movement, including the positioning of the body in space, limb angles, etc. (Eaves et al, 2012).

2.5 Evidence of Motor Representation in Action Observation

2.5.1 Motor Resonance Theory

It has long been hypothesized that learning via observation is due to the involuntary activation of a motor representation that is comparable to physical execution (Shepard, 1989). Motor resonance theory can be used to explain how the observation of a movement is able to enhance subsequent performance outcomes. Motor resonance theory states that the observation of a movement results in the activation of perceptual and motor systems in the observer without physically executing the movement (Jacob, 2009; Saxe 2005). When a movement is observed, the observer's perceptual system is active and subsequently elicits activity of neurons in the motor system, allowing for the translation from external movement information to an internal representation of movement. Therefore, motor resonance can be thought of as the observer simulating the observed movement in order to acquire understanding of the movement by translating the perceptual representation into a motor representation (Figure 4; Uithol et al., 2011). This intrapersonal resonance between the observer's motor system and the movement observed is possible because specific neurons involved in the movement are activated in the primary motor cortex during the physical performance of the movement as well as the observation of the movement being performed (Gallese & Goldman, 1998).

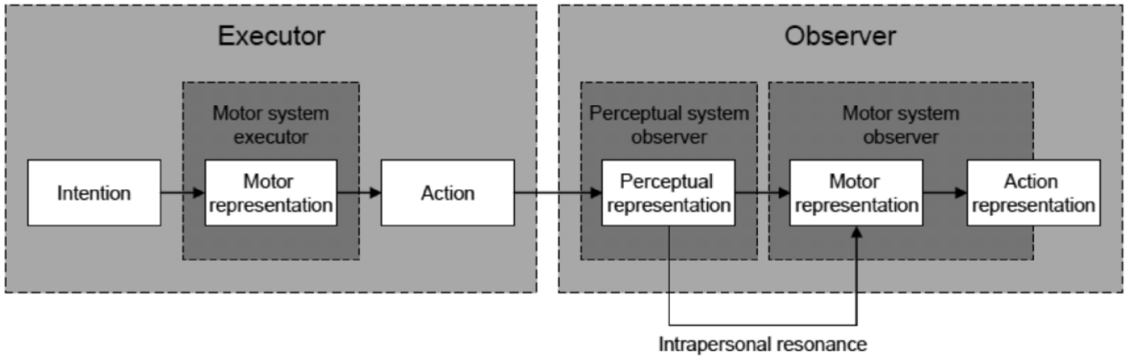


Figure 4. The path between action intention to action execution in the executor and perceptual representation to action representation in the observer. Intrapersonal resonance is the formation of a motor representation from a perceptual representation of movement. Adapted from Uithol et al., 2011.

2.5.2 Mirror neurons

Initial evidence of motor resonance comes from studies examining the mirror neuron system in the premotor and parietal cortex of the macaque monkey; this and subsequent work showed that neurons specific to a movement are not only active when the primates were executing the movement, but that the neurons were also active when they were observing the movement being performed (see Figure 5; Gallese et al., 1996). These finding show mirror neurons are action specific, playing an important role in understanding others' movements.

Neuroimaging studies have extended these findings, revealing a similar class of mirror neurons are present in humans, specifically in the inferior parietal lobule, ventral premotor cortex, and part of the inferior frontal gyrus (Ste-Marie et al., 2011). Essentially, these neurons process incoming sensory information (i.e. observing a hand movement) and transform this information into a motor representation of the movement by eliciting the corresponding mirror neurons in the motor cortex. These findings suggest that AO is likely to play a role in understanding the intention and goal of an observed action, thus providing a perceptual component to the simulation of a motor representation (Fabbri-destro & Rizzolatti, 2008).

Figure 5. Mirror neurons of a reaching and grasping hand movement. Neurons are active when the primate observes the reaching movement (a); the same neurons are active when the primate executes the movement (b); Gallese et al., (1996).

Neurophysiological studies have provided more in-depth theory into the role mirror neurons play in humans. Fadgia (1995) measured corticospinal excitability via MEPs in the finger flexor muscles using TMS in order to investigate whether observing a finger tapping movement would facilitate the same neural components in the observer that would be active in the person executing the movement. Observation of finger tapping did indeed elicit strong facilitation of MEPs in the finger flexor muscles during the observation of finger movements. Furthermore, MEP patterns during observation mirrored MEP patterns during execution of the same movement, demonstrating that AO stimulates similar motor regions involved in movement as physical execution. Additionally, Hardwick and colleagues (2012) found that the deliberate observation of a grasping movement, with the intent to subsequently execute the movement, resulted in increased amplitude MEPs when compared to passive observation of a movement. Importantly, passive observation also resulted in increased corticospinal excitability compared to rest, however to a lesser degree than deliberate observation. In both conditions, passive and deliberate observation, there was no effect on corticospinal excitability in an unrelated control muscle. It is evident from these findings that the observation of an action primes the motor system of the observer that is similar to neurophysiological changes present during PP. These findings suggest that while mirror neurons play a role in action perception (e.g. understanding the intention and goal of a movement) they may also contribute to subsequent facilitation of the movement being observed.

The abovementioned findings have fueled efforts for further research into the role AO plays in action facilitation. Performance studies such as Rizzolatti & Sinigaglia (2010) and Springer (2013) investigated the subsequent physical performance of participants that observed an expert performing a movement. They found observers matched the kinematics of the expert, such as the speed of the movement and the positioning of their limbs in space. These findings not only provide further evidence that AO elicits a response in the mirror neurons of the respective action but creates an internal bottom-up motor representation of the sensory information of the action, encoding temporal and kinematic information (Boronii 2005; Rizzolatti and Sinigaglia 2010). Matching of temporal information also occurs when observation is passive, however to a lesser extent. That the matching of temporal information also occurs when observation is passive is important to note as it shows the automatic nature involved during observation for sensory processing of actions. Therefore, AO produces learning by relying on the same mechanisms as physical execution in order to simulate a motor representation without physical performance (Jeannerod, 2001).

2.5.3 Neural components of action observation

Action observation consistently recruits a bilateral network of premotor and parietal regions similar to MI, however greater activation is seen bilaterally (Figure 6). A distinct cluster of neural regions have been identified to be active during AO including the ventral and dorsal premotor cortex and visual temporal and posterior parietal regions of the somatosensory cortex.

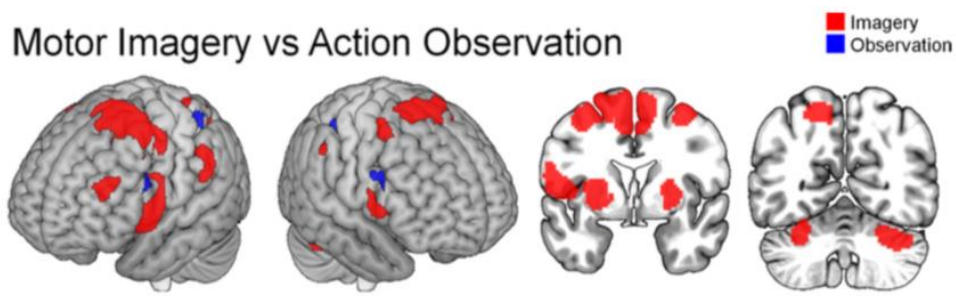


Figure 6. Activation patterns distinct to AO compared to MI determined via conjunction analysis of 303 neuroimaging studies. Adapted from Hardwick et al., (2018).

While overlapping recruitment for AO and physical execution was seen in the bilateral premotor, parietal, and sensorimotor network, as well as clusters found in premotor regions, including the pre-sensory motor area, bilateral ventral premotor and dorsal premotor cortexes (Figure 7). While there is considerable overlap between regions in AO and physical execution, upon further analyses, Hardwick and colleagues found that a small cluster of activation in the cerebellum, active during both AO and physical execution, may not be directly recruited during AO but instead a result of indirect recruitment stemming from the visual cortex's involvement in AO for generating a motor representation.

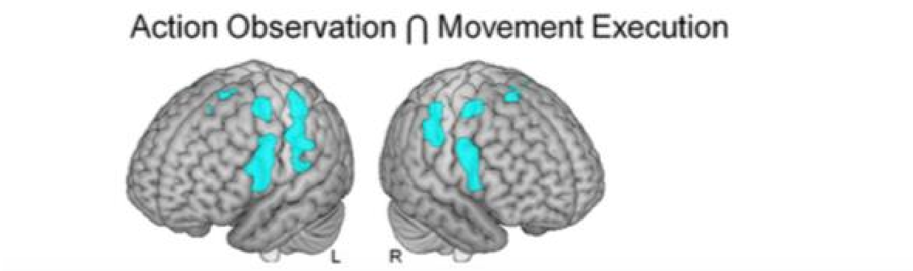


Figure 7. Overlapping brain regions (bilateral premotor, parietal, and sensorimotor network, as well as clusters found in premotor regions) recruited during AO and physical execution, determined via conjunction analyses of 303 neuroimaging studies, relative to PP controls. Adapted from Hardwick et al., (2018).

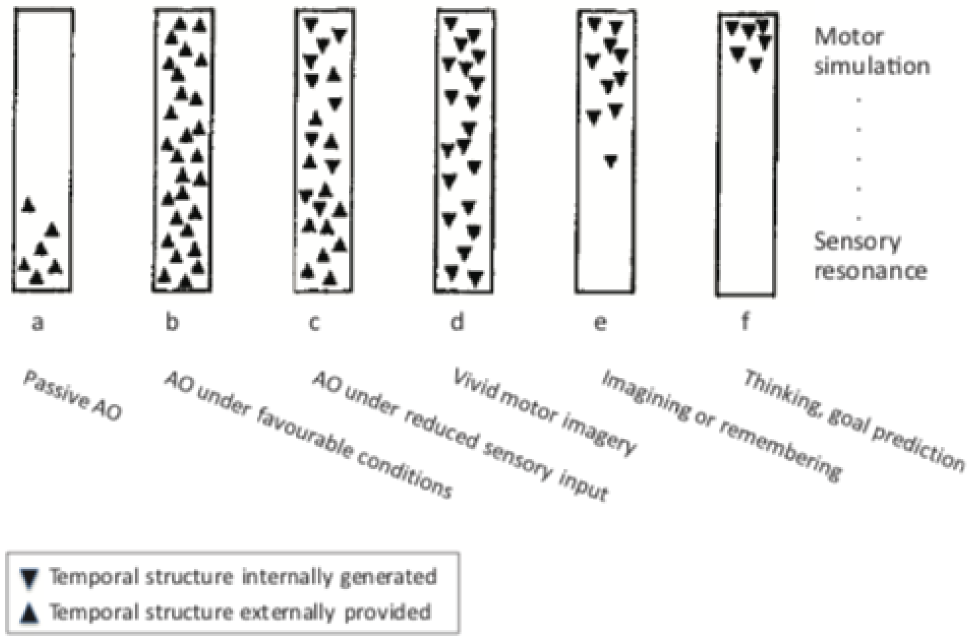
2.6 Impetus for the Simultaneous use of MI and AO for Motor Learning

2.6.1 Behavioural evidence for the use of AO+MI for motor learning

Although AO and MI have typically been applied as independent modalities in the field of motor learning, researchers have begun to take a multimodal approach implementing the simultaneous use of AO and MI (AO+MI) in motor learning studies (Romano-Smith 2018; Wright et al., 2018; Bishop et al., 2020). Initial behavioural evidence for AO+MI comes from sport performance studies that utilized video recordings of movement in order to decrease the cognitive load of internally generating an image, allowing for increased attentional focus on the kinesthetic sensation of the movement during MI, while the video provided the external representation (Holmes et al., 2004, 2006). MI instruction combined with the AO aspects of video guidance for a golf putt resulted in greater performance outcomes for both accuracy and kinematic variables compared to MI alone. Extending these findings, Wakefield and colleagues (2018) conducted a six-week darts training study in which participants trained three times a week using one of the five training modalities: MI, AO, simultaneous AO+MI, alternating AO and MI, and PP. Post-training, greater performance outcomes were seen in the simultaneous AO+MI group compared to AO and MI in isolation. Performance of the alternating AO and MI group was greater compared to the AO group, but not the MI group, a finding that suggests the simultaneous nature of AO+MI has a greater effect on learning compared to when the modalities (AO and MI) are applied separately from one another. These findings suggest that the simultaneous use of AO+MI must be eliciting greater neural activation of the motor network and corresponding regions, in order to account for increased learning outcomes.

2.6.2 Dual-action simulation hypothesis

AO relies on external sensory information in order to simulate a movement, resulting in a stimulus-oriented representation that is perceptually based. MI relies on an internal motor simulation of movement that is stimulus-independent and cognitively based. Although AO and MI are two distinct motor representations, there is an overlap of sensory (external) and motor (internal) representational processes that exist on a continuum (Figure 8).



*F*igure 8. Motor imagery and AO represented as a continuum from motor simulation to sensory resonance. AO and MI differ in temporal structure: bottom-up and top-down, respectively. 'b' represents the ideal AO condition (observation of movement in first person) while 'd' represents the ideal MI condition (kinesthetic imagery). Adapted from Vogt et al., (2013).

The dual-action simulation hypothesis suggests that the cognitive processes involved in the external simulation of a movement (AO) and perceptual processes involved in the internal simulation of movement (MI) can exist simultaneously in the brain, eliciting an enhanced generation of the motor representation. Under this hypothesis, AO+MI is thought to elicit a greater motor simulation response due to the activation of multiple motor regions distinct to each modality, as well as the potential of greater activation in the overlapping regions involved in both processes.

2.6.3 Neurophysiological and imaging evidence for the use of AO+MI for motor learning

Meta-analysis of neuroimaging studies has found considerable overlap between neural regions involved in physical execution, AO and MI (Swinnen, et al., 2018; Hardwick 2019). Specifically, conjunction analyses of AO and MI revealed recruitment of the bilateral premotor and rostral parietal regions, including greater cortical volume seen in the left hemisphere (Figure 9). Additionally, activation was seen in both AO and MI in the primary motor cortex and bilateral clusters in the dorsal and ventral premotor cortex. While motor simulation via AO and MI share many overlapping neural regions, each modality relies on distinct neural areas in order to form a motor representation. For instance, AO relies on a large range of processes outside of MI, such as external sensory processing and perception necessary for recognition, as well as understanding (Rizzolatti & Sinigaglia 2010) and predicting actions (Springer et al., 2013), While the nature of MI involves recruitment of more cognitive-driven regions including pre-frontal areas, as well as motor-related regions such as the cerebellum, in order to form an internal motor representation.

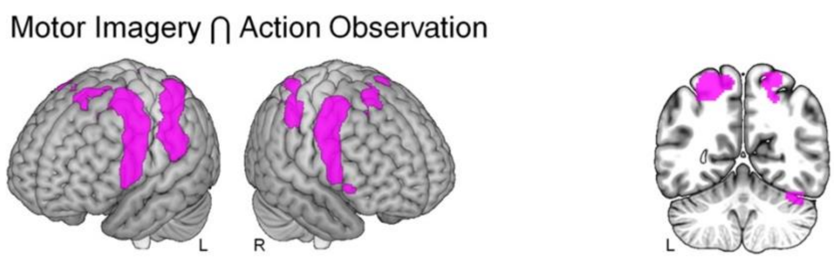


Figure 9. Overlapping brain regions (primary motor cortex, bilateral clusters in the dorsal and ventral premotor cortex, bilateral premotor and rostral parietal regions) recruited during AO and MI, determined via conjunction analyses of 303 neuroimaging studies, relative to PP controls. Adapted from Hardwick et al., (2018).

Studies that have investigated neural processes behind AO+MI have provided evidence that supports the dual-action simulation hypothesis, showing greater activity of the motor execution network during AO+MI, than either one in isolation (Eaves, Riach, Holmes, & Wright, 2016). Evidence of this is particularly prominent in neuroimaging studies of the sensorimotor area, with finding of greater activation during AO+MI, suggesting that the combination of AO+MI allows for AO to offload MI by supporting the internal generation of imagery via observation, allowing for increased focus on the kinematic sensations associated with the movement (Macuga & Frey, 2012; Nedelko et al., 2012).

While the extent to which each individual modality contributes to the increased activity seen during AO+MI is still unknown, these two motor simulation modalities, when used simultaneously, seem to recruit overlapping neural areas to a greater extent while contributing their respective individual neural networks in forming a motor representation. While neuroimaging studies offer insight into the neural regions recruited and contributing to motor simulation during AO+MI, neurophysiology studies have provided insight into the physiology behind greater learning outcomes seen during AO+MI compare to AO or MI alone. If AO+MI results in greater learning outcomes, measures of the neural response to the modality, such as corticospinal excitability, should be of increased magnitude during AO+MI. While prior learning studies investigating corticospinal excitability during AO+MI have shown MEPs with significantly higher amplitude during AO+MI compared to AO alone, some have reported similar results for AO+MI compared to MI (Franklin et al., 2018, Holmes et al., 2014), while others have reported conflicting results showing AO+MI does not result in greater amplitude MEPs compared to AO or MI alone (Eaves et al., 2016; Wright et al., 2014; Fadiga et al., 1999). These conflicting results suggest that it is likely AO or MI are not contributing equally to the motor representation, and one modality may be driving the increased behavioural outcomes seen during AO+MI. Vogt and colleagues (2020) investigated the neurophysiology behind performance outcomes during AO+MI by measuring corticospinal excitability (i.e. MEPs) during a finger sequence task performed via congruent AO+MI (stimulus observed matched imagery instruction) and incongruent AO+MI (stimulus and imagery instruction did not match). While findings showed higher amplitude MEPs for the congruent AO+MI condition, it is important to note that the incongruent AO+MI condition included an incongruent AO variable, not an incongruent MI variable. While the authors draw conclusions that MI is driving AO+MI, it is difficult to support these findings when the incongruent AO+MI condition favored MI. Additionally, results were compared to a baseline condition (MEPs during rest) and an AO only condition, but not an MI only condition.

While behavioural studies have provided clear evidence of greater learning outcomes when AO and MI are applied simultaneously, literature investigating the neurophysiology behind the increased performance outcome provides inadequate methodology for investigating the neurophysiological underpinnings that produce learning. To date, no motor learning study has included both components of AO+MI individually, while investigating the neurophysiology behind behavioural performance. By comparing cortical activity during AO+MI with only one of the modalities in isolation the link between neurophysiology driving the increased learning outcomes of AO+MI cannot be fully evaluated.

Chapter 3: Proposed Study Rationale and Objective

3.1 Rationale

While studies have investigated the neural mechanisms and behavioural outcomes of AO+MI, to date, previous studies have failed to investigate AO+MI alongside MI and AO independently at both the neural and behavioural level. Therefore, it is difficult to draw a complete understanding of the neurophysiological effects of AO+MI that facilitate changes in the brain which drive greater performance outcomes compared to AO and MI alone. If AO+MI elicits greater learning outcomes, evident through behavioural measures, AO+MI should elicit a greater neural response via increased corticospinal excitability compared to AO and MI independently. This research aims to bridge our understanding of the underlying neurophysiology elicited during AO+MI that facilitates changes in the motor cortex, creating an environment conducive to learning and resulting in the subsequent enhanced performance, evident through behavioural outcome measures, compared to AO and MI independently.

To address the purpose of the current study, a scoping review was implemented to provide an overview of the research findings related to the effect of MI, AO and AO+MI on corticospinal excitability. A scoping review was deemed to be the most appropriate type of review to conduct because a scoping review allows for the examination of how AO, MI and AO+MI research is conducted (e.g. instruction type, session length), identification of gaps in current literature and as a precursor to a systematic review (Munn et al., 2018). While there is a degree of overlap between scoping reviews and systematic reviews, a key distinguishing factor is the overarching goal of a systematic review is to address the effectiveness of a particular practice or treatment implemented, which in this case would be the application of AO, MI and AO+MI for motor learning and the effect of AO, MI and AO+MI on corticospinal excitability (Munn et al., 2018). As outlined above, literature on this topic is not currently at a stage of knowledge that would warrant a systematic review (informing application of AO, MI, and AO+MI), due to the discrepancy between neurophysiological findings as well as the variability of methodological parameters across studies. By implementing a scoping review as the design for the current study we are able to investigate both broad and narrow questions related to the effect of modality on corticospinal excitability and the methodological factors that may influence increased corticospinal excitability, while addressing areas within both of these questions where information is lacking or unknown. Additionally, a scoping review of literature contributes to and extends pasts narrative reviews on AO, MI and AO+MI, such as a review by Eaves and colleagues (2018) that provided an overview of theory and evidence for the use of AO, MI and AO+MI for motor learning by providing a narrative summary of theories and concepts in order to fuel future inquiries in the area of AO+MI (Green et al., 2006)

Since the primary focus of the review was to investigate the effect of AO, MI and AO+MI on corticospinal excitability, the primary motor cortex is the focus as changes in excitability, measured using TMS (via MEPs), is achieved by stimulating the region of the primary motor cortex responsible for the given movement (e.g. stimulating the hand knob region when performing imagery of a finger abduction movement). Assessing changes in excitability via the primary motor cortex is widely used across studies investigating the neurophysiological effects of AO, MI, and AO+MI on the brain because the primary motor cortex is within range of area the electromagnetic current can stimulate (Hallett, 2007). As mentioned above, multiple neural regions outside of the primary motor cortex are active during AO, MI, and AO+MI, however, these regions are largely inaccessible to the application of TMS. While this possess a limitation in terms of the extent to which this review can investigate the neurophysiological effect AO, MI and AO+MI has on the brain, by assessing changes in excitability via the primary motor cortex we are able to deduce the extent to which each modality activates neurons that are responsible for the execution of the movement.

3.2 Objective

The overarching objective of the scoping review is to investigate the effect of AO, MI and AO+MI on corticospinal excitability during a motor-related task (i.e. any task that involves human movement), with a secondary objective of identifying methodological factors (e.g. task type, session length) that influence increased corticospinal excitability.

Chapter 4: Methodology

4.1 Search Strategy

A scoping review of literature related to imagery and observation was performed in order to identify articles investigating the effect of MI, AO, and AO+MI on corticospinal excitability. Medline, CINAHL, EMBASE and SPORTdiscus databases were electronically searched from inception to June 24th, 2020 using a combination of subject headings and keywords related to the main themes of the scoping review: MI, AO, AO+MI, TMS, and corticospinal excitability (see Appendix A for full search). Search terms were developed in collaboration with the research team as well as from keywords listed in review papers and publications on MI, AO, AO+MI, and TMS. The search strategy was developed through collaboration with an information services librarian and peer-reviewed by a second librarian using the PRESS (Peer Review of Electronic Search Strategies). Our protocol, including search strategy, inclusion criteria, screening strategy, and data extraction was developed a priori using the Preferred Reporting Items for Systematic Reviews and Metanalyses (PRISMA-P-ScR) guidelines for scoping reviews (Tricco et al., 2018, detailed protocol can be found in Appendix B).

4.1.1 Inclusion/ Exclusion Criteria

Inclusion of studies was determined via a multi-step process. Inclusion criteria included: (1) Population: studies including healthy adult participants (>18 years old); (2) Intervention: TMS used to measure corticospinal excitability during AO, MI and AO+MI of a motor task; (3) Procedure: AO, MI and AO+MI clearly defined, including type of imagery (kinesthetic vs. visual), length of training and task performed; (4) Outcome: application of TMS to measure the effect of training modality on corticospinal excitability;

and (5) Study Design: studies were not limited by their design; all levels of evidence were included in the final review. Papers were excluded based on the following criteria: (1) Studies not accessible in the English language; (2) studies that included participants < 18 years old; (3) studies that included clinical populations as the subject group; (4) studies that applied a between group design (except for group modality: AO, MI AO+MI); (5) studies that applied incongruent AO+MI instead of congruent AO+MI; (6) studies that had an experimental manipulation of the task (e.g. included emotional salience, a social component, manipulated force requirements, positioning of participant, etc.); and (7) studies that do not clearly report outcome measures of TMS (i.e., MEPs or standardized % of MEPs). Note that exclusion criteria 4, 6, and 7 were added to phase two screening following a brief review of articles that met initial phase two screening (study design criteria 1-3 and 5) due to the large volume of articles that did not clearly report a quantifiable outcome for MEPs, as well as studies that were primarily interested in an additional factor and thus included an experimental manipulation of the task (e.g. changing the the emotional state of an individual performing a movement that was then observed by the participant).

4.1.2 Screening Strategy

All databases were searched on June 24th, 2020 and the results were uploaded to Covidence. Duplicates were identified and removed automatically (via Covidence). Following the removal of duplicates, articles underwent a three-phase screening process by two individual reviewers; any conflicts were resolved by a third reviewer. The three-phase screening process consisted of separate inclusion and exclusion criteria for phase one and phase two. An initial screening (phase one) of titles and abstracts was done with broader inclusion and exclusion criteria in order to narrow down the scope of articles for the full text review (phase two), while not limiting articles included due to not meeting more narrow inclusion and exclusion criteria in the title and abstracts that would be included in the full text. Initial screening consisted of screening the title and abstracts of articles (see Appendix C for detailed inclusion/ exclusion criteria and screening phases). At this phase, articles were included if they were in the English language, included healthy participants (non-clinical), and imagery and/or observation were applied to a motor-related task. All articles that did not meet the inclusion criteria were excluded. Articles that met phase one inclusion criteria were reviewed in full text during phase two. During phase two, articles were screened and included if the motor-related task involved the use of the upper limb; the AO+MI group (if included), was congruent and performed simultaneously; TMS was used to measure corticospinal excitability; and the measure of excitability was clearly quantified and reported (peak MEP, MEP percentage, z-score, mean MEP). A third phase was included in order to address the issue of availability of data to extract and include in the review, as well as to narrow the scope of the review to deal specifically with studies related to the stated objective. As such, during phase three, articles were excluded if the study utilized a between-group design (with the exception of task modality); the task being performed included a manipulation (e.g. manipulation of effort, social/ emotional context, environmental conditions); or if corticospinal excitability was not reported as a raw voltage value or expressed as a percentage of a baseline value (i.e., a normalized percentage). Articles that did not meet phase three criteria were rejected and not included in data extraction

4.1.3 Data Extraction

Data was extracted by two reviewers using the data extraction template created a priori (Appendix D). Information pertaining to the study population such as age, sex, handedness, MI ability assessment, and familiarization to task was extracted in order to characterize the study populations that are encompassed in the present review. Task specific information such as imagery or observation modality used, modality instruction, motor-related task applied, length of session, and length of total exposure were included to characterize any similarities and differences across studies. Mean MEP amplitude during task and rest or the normalized percentage of the MEP, were recorded in order to plot corticospinal excitability across all study groups. Data extraction was assessed for bias using the Critical Appraisal Skills Programme (CASP; Appendix E), and any discrepancies in data were resolved by a third extractor.

4.1.4 Synthesis of Results

All experimental information pertaining to participant population and task, as mentioned in detail above, was tabulated. Data for experiments with multiple conditions of imagery or action observation (e.g. Meer's and colleagues 2020: AO and AO+MI of index finger flexion as well as AO and AO+MI of thumb flexion in the same study) were tabulated separately (e.g. Meers 2020 A, Meers 2020 B). A plot was created across all studies showing the relationship between corticospinal excitability (difference in MEP amplitude at task and at rest) and modality (AO, MI and/or AO+MI) used in the study. Plots were also created based on methodological factors (complexity of skill, statistical significance of study) in order to investigate the factors that contribute to increased excitability across conditions.

Chapter 5: Results

5.1 Studies Selected

The initial search of the electronic databases returned 1138 articles (see Appendix F for PRISMA diagram). Following the removal of duplicates, a total of 705 articles remained and were subjected to stage one screening. Following stage one screening, 327 articles remained and were subsequently reviewed in full text during phase two. Upon completion of phase two, 105 articles remained. During phase three screening, 84 articles were excluded. The remaining 21 articles were included in data extraction. All studies included were deemed to clearly address a focused research question, include sound methodological design, and report valid results, as determined via the CASP assessment.

5.2 Study Characteristics

Detailed information pertaining to participant and methodological characteristics of the studies included in the review are presented in Tables 1, 2 and 3, and are summarized below.

5.2.1 Participant Characteristics

The final review included a total pooled sample of 319 participants, 178 of those participants engaged in MI, 91 engaged in AO, and 41 engaged in AO+MI. The average number of participants per study was 14 (range: 8-21; Table 1). Thirteen studies consisted of exclusively right-handed participants and four studies included both left- and right-handed participants, while four studies did not report participants' handedness. Mean age of participants across all studies was 26.5 years (range 21-36). Nine of the 18 studies that included an MI condition (either in isolation or MI+AO) assessed participants' MI ability. Four of the nine studies assessed participants' MI ability via the Motor Imagery

Questionnaire (MIQ), two studies assessed imagery ability via the Kinesthetic and Visual Imagery Questionnaire (KVIQ), two studies assessed imagery via verbal report of imagery experience, and one study assessed imagery ability via the Visual Imagery Movement Questionnaire (VIMQ) and a hand rotation task. A total of eight studies had paradigms in which participants had prior exposure to the task, either via imagery, observation or physical execution (six MI groups, two AO groups, two AO+MI groups).

Table 1. Participant characteristics across the 21 studies included in the review.

Identification			Population						
Study #	Author	Year	Handedness		Sex		Age	MI assessment	Assessment type
			RH	LH	M	F	Mean	Y/N	
1	Aono	2013	12	0	7	5	36	N	
2	Aoyama	2019	13	0	NR	NR	21	Y	KVIQ
3	Aoyama	2016	14	0	7	7	21	Y	KVIQ
4	Cengiz	2016A	12	0	10	2	33	N	
5	Cengiz	2016B	12	0	10	2	33	N	
6	Fourkas	2006A	28	2	12	18	NR	Y	verbal report
7	Fourkas	2006B	28	2	12	18	NR	Y	verbal report
8	Hayashi	2002	9	0	9	0	NR	N	
9	Lago	2011	NR	NR	11	5	21	N	
10	Liang	2014	11	0	10	1	23	N	
11	Oku	2011	NR	NR	9	1	NR	N	
12	Ray	2013	11	1	9	3	26	N	
13	Rozand	2014	NR	NR	10	0	28	Y	MIQ
14	Stinear	2003	7	1	5	3	31	N	
15	Stinear	2004	8	0	5	3	33	N	
16	Williams	2012	15	0	5	24	29	Y	VIMQ, Hand rotation
17	Wright	2018	18	0	18	0	22	Y	MIQ
18	Yoxon	2020	26	0	6	20	23	N	
19	Gueugneau	2014	NR	NR	5	9	26	N	
20	Meers	2020A	13	0	3	10	23	Y	MIQ
21	Meers	2020B	13	0	3	10	23	Y	MIQ

5.2.2 Intervention Characteristics

Sixteen of the 21 studies included a single group (two AO, 14 MI). One study included MI and AO groups, two studies included AO and AO+MI groups, and two studies included MI, AO, and AO+MI groups (Table 2). All of the studies included in the review implemented a single session design. Session length was reported for four of the 21 studies (range 7-90 minutes).

Table 2. Study design for the 21 studies included in the review. Shaded area represents the presence of that category in the study.

Identification		Study Design					
Author	Year	Study	Design		Groups		
			With-in	Between	MI	AO	AO+MI
Aono	2013	1	■		■		
Aoyama	2019	2		■			■
Aoyama	2016	3		■	■		
Cengiz	2016A	4	■		■		
Cengiz	2016B	5	■		■		
Fourkas	2006A	6	■		■		
Fourkas	2006B	7	■		■		
Hayashi	2002	8	■		■		
Lago	2011	9	■			■	
Liang	2014	10	■		■		
Oku	2011	11	■		■		
Ray	2013	12	■			■	
Rozand	2014	13		■	■		
Stinear	2003	14		■	■		
Stinear	2004	15		■	■		
Williams	2012	16		■	■	■	
Wright	2018	17	■		■	■	■
Yoxon	2020	18	■		■		
Gueugneau	2014	19		■		■	
Meers	2020A	20		■		■	■
Meers	2020B	21		■		■	■

5.2.3 Motor Imagery

Of the 16 studies that included a MI group, three studies did not report imagery perspective used (first person perspective: participants imagining themselves perform the movement; or third person perspective: imagining someone else perform the movement), 15 reported the use of first person imagery, seven of the 15 studies reported first person imagery was paired with kinesthetic imagery instruction (imagining the kinesthetic sensation of performing the movement), the remaining eight studies did not report imagery instruction used. One study reported the use of third person imagery perspective but did not report imagery instruction used. Four of the 16 MI groups implemented imagery of a complex movement task(s) (e.g. reaching and grasping task, basketball free-throw), while twelve studies used simple movement task(s) (e.g. finger flexion, abduction and adduction). There was a total of seven different tasks across the 16 MI-based studies, ranging from one to three tasks per study, with an average of 1.2 tasks per study. Finger abduction and adduction was the most commonly used MI task, being present in six studies, and basketball free throw was the least commonly used task, being present in one of one of 16 studies.

5.2.4 Action Observation

Of the six AO groups, three implemented first-person observation, (e.g. viewing a movement that corresponds with how they would see the movement executed if they were to perform it) and three studies implemented third person observation (e.g. viewing the movement from the perspective of another person executing the movement). Three of the AO groups included complex movement task(s) as the observed movement (e.g. basketball free throw) while three included simple movement task(s) (e.g. finger flexion). There was a total of six different type of tasks presented via video to participants across the six AO-based studies. All studies implemented a single observation task. Reaching and grasping was the most commonly used type of task, being present in three of the six AO studies, while thumb-finger opposition and basketball free-throw were the least commonly used type of task, each present in one study.

5.2.5 Action Observation + Motor Imagery

Across the four AO+MI-based studies, three studies implemented first-person observation simultaneously with kinesthetic imagery, where participants viewed the movement from the first-person perspective (e.g. viewing the movement from the perspective they would see if they were executing the movement) while imagining themselves performing the movement. One study implemented third person observation (viewing someone else perform a movement) simultaneously with kinesthetic imagery.

One AO+MI study included a complex movement (basketball free throw), while three studies implemented simple movement task(s) (e.g. finger flexion). There was a total of three different AO+MI tasks, ranging from one to two tasks per study, with an average of 1.5 tasks per study. Finger flexion was the most commonly used type of task, being present in two of the four studies, while finger abduction/adduction and basketball free throw were each present in one study.

5.3 Overall Findings

5.3.1 Effect of modality type on corticospinal excitability

Figure 10 shows the difference between mean MEP amplitude during rest and task across studies for the AO, MI and AO+MI conditions. Thirteen of the 16 MI groups reported MI to have a significant effect on MEP amplitude, in that MEP amplitude was increased during task relative to rest (baseline). Two of the six AO groups reported AO to have a similar effect as MI on MEP amplitude, in that MEP amplitude was significantly higher during task relative to rest. All four AO+MI groups reported a significant increase in MEP amplitude during AO+MI compared to rest. There are no clear methodological distinctions between the groups that did not find a significant effect of AO or MI on corticospinal excitability and the groups that did, with similarities of task type, prior exposure, and modality instruction (Table 3).

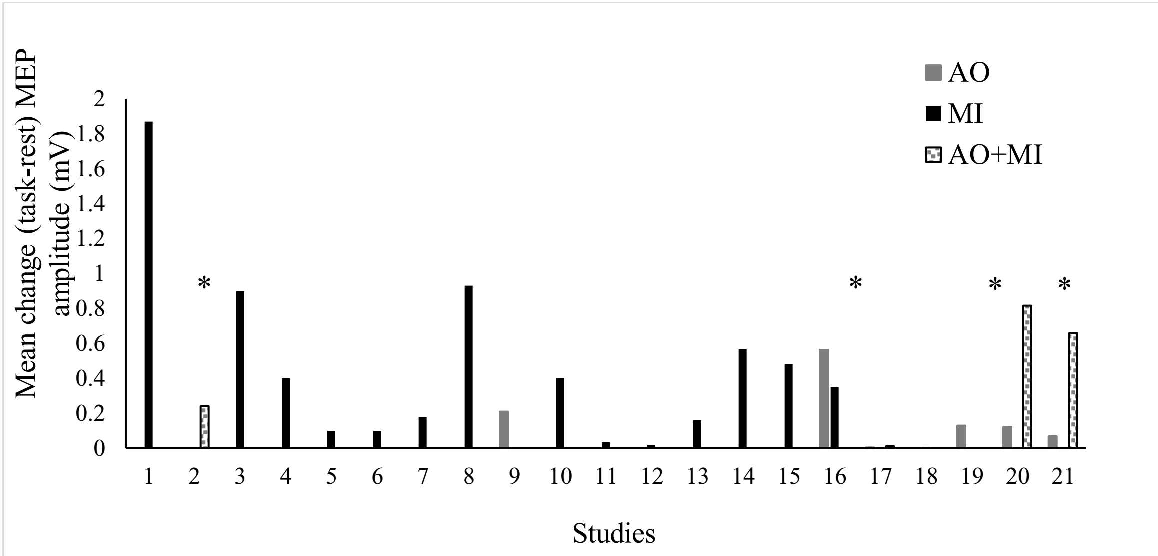


Figure 10. Change in MEP amplitude (mV) (MEPs obtained during task - MEPs obtained during rest) across all conditions (AO, MI, AO+MI) in 26 different groups. Groups that did not report a statistical significance of modality type on corticospinal excitability (study 2, 17, 20 and 21) are denoted by an asterisk (*). Note that studies 2, 16, 20 and 21 have multiple conditions; not all conditions resulted in a change in mean MEP amplitude large enough to be observed on the figure.

Table 3: Methodological characteristics across the 21 studies included in the review and displayed in Figure 11. Shaded area represents the presence of the characteristic in the study.

Study	Prior exposure to task	Imagery perspective	Imagery instruction		observation perspective	
		1st or 3rd person	KIN MI	VIS MI	1st AO	3ND AO
1		1st person	NR	NR		
2		1st person				
3		1st person				
4		1st person	NR	NR		
5		1st person	NR	NR		
6		1st	NR	NR		
7		3rd person	NR	NR		
8		1st person				
9		NR	NR	NR		
10		1st person	NR	NR		
11		1st person				
12		NR			NR	NR
13		1st person				
14		1st person	NR	NR		
15		1st person	NR	NR		
16		1st person				
17		1st person				
18		1st person	NR	NR		
19		NR	NR	NR		
20		1st person				
21		1st person				

Of the four studies that included an AO+MI group, across all four studies AO+MI had a significant effect on corticospinal excitability, resulting in increased MEP amplitude (Figure 11). While the AO conditions, present in three of the four studies, as well as the MI condition, present in one of the four studies, did not have a significant effect on MEP amplitude.

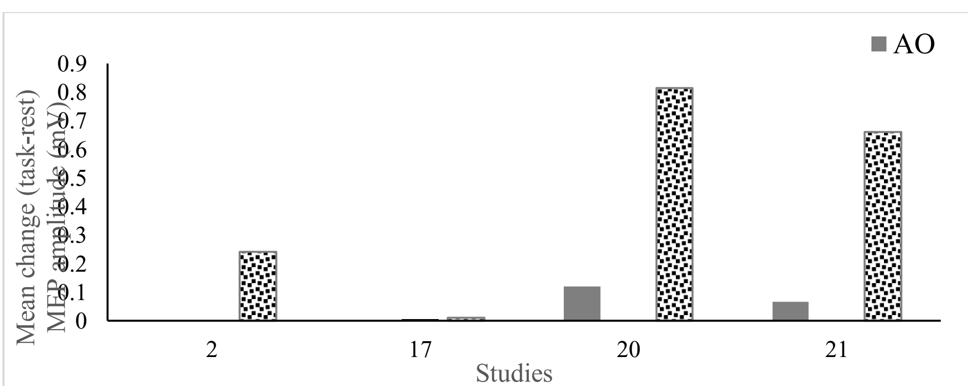


Figure 11. Mean MEP change (task-rest) of all groups included in studies that had an AO+MI condition.

5.3.2 Methodological factors that influence corticospinal excitability

Of the 26 different groups included across the 21 studies, 20 groups found a significant effect of modality type (AO, MI or AO+MI) on corticospinal excitability (increased excitability during task compared to rest; Figure 10).

In order to further investigate the effect methodological factors have on corticospinal excitability, studies were grouped based on complexity of the task(s) implemented (simple movements: flexion/extension, abduction/adduction or complex movements: reach and grasping, basketball free-throw; Figures 12 and 13, respectively) across all modality groups (AO, MI, AO+MI). No clear difference can be seen between studies that used simple movement tasks compared to studies that used complex movement tasks for AO and MI groups. However, for the AO+MI groups, there is a difference between the complex movements and simple movements, with simple movement tasks for AO+MI resulting in increased MEP amplitude to a larger degree than MEP amplitude when complex tasks were performed via AO+MI.

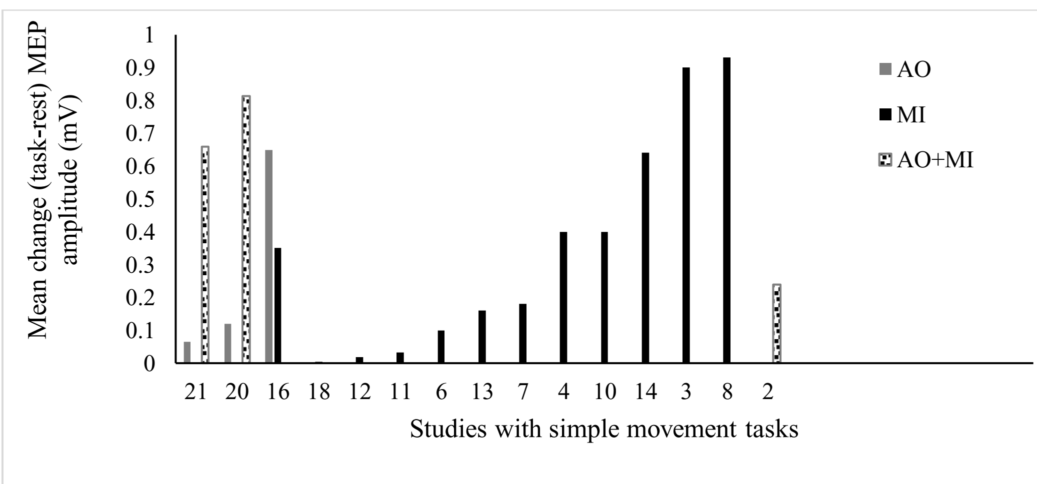


Figure 12. Change (task-rest) in mean MEP amplitude for studies that found a statistically significant effect of modality type on excitability during a simple movement task. Studies 21, 20, and 16 had multiple modality groups.

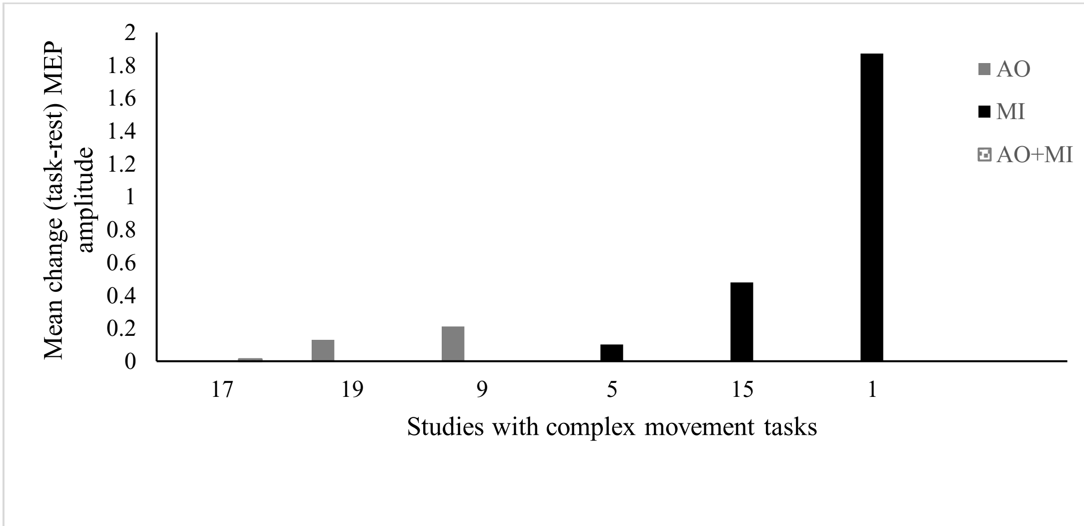


Figure 13. Change (task-rest) in mean MEP amplitude for studies that found a statistically significant effect of modality type on excitability during a complex movement task. Increased excitability during task is seen to be greatest during MI and AO, while increased excitability is minuet during AO+MI (study 17).

Chapter 6: Discussion

6.1 General Discussion

The findings of the present review support prior literature that has found MI, AO and AO+MI have an effect on corticospinal excitability, resulting in increased MEP amplitude during task compared to rest. As previously reported (Eaves 2016), and highlighted by the current study, these findings hold true across various conditions, including task type, imagery and observation perspective, and modality instruction.

The overarching goal of the present scoping review was to identify the relationship between modality type (AO, MI, AO+MI) and corticospinal excitability (via MEPs), with a particular interest in the effect AO+MI has on corticospinal excitability, that may highlight the underlying neural processes that result in increased behavioural outcomes which ultimately produce learning that previous studies have reported (Romano-smith 2018; Wright 2016). While the four AO+MI groups included in the review consistently found AO+MI to result in increased MEP amplitude relative to rest, the three MI studies and four AO-based studies did not find a significant effect of modality on MEP amplitude. No clear distinction between methodological factors and modality were able to be identified that may explain the discrepancy between MI+AO findings and AO and MI findings of similar tasks. For example, Meers and colleagues (2020) found no significant effect of AO during first person observation of a finger flexion task, however they found AO+MI to have a significant effect of the same task. A methodologically similar study by Aoyama and colleagues (2019) found a significant effect of AO during first person observation of finger abduction and adduction. Both studies were single sessions and did not include prior exposure to the task, however their findings regarding the effect AO has on corticospinal excitability greatly differ. Investigation of the intensity of stimulator output may provide further insight into the inconsistent findings between studies that have employed similar methodological parameters. If one study applied stimulation at a higher percentage of RMT, this could account for the increase in corticospinal excitability, that would not be present if stimulator output was a lower percentage.

While AO+MI significantly increased corticospinal excitability in all studies included in this review, studies that compared AO+MI groups to AO or MI independently did not find AO or MI to have an effect on excitability on their own. If AO+MI results in greater performance outcome it is plausible that this is due to the simultaneous recruitment of neural regions involved in both AO and MI that contribute to the internal generation of a motor task. This is important to note because if increased excitability during AO+MI, which is a precursor for enhanced performance, is a result of the individual modalities, it would be expected to see a similar effect of each modality on corticospinal excitability when applied individually, albeit to a lesser degree. However, the present review highlights that prior studies that have compared AO+MI to AO or MI groups have not found AO or MI to independently facilitate corticospinal excitability. Therefore, whether the simultaneous use of AO and MI results in greater recruitment of overlapping neural regions, as well as their respective regions, is still largely unknown and no conclusions can be drawn regarding whether one modality may be driving the neurophysiological changes that result in enhanced behavioural outcomes prior studies have reported when implementing AO+MI. Additionally, the absence of increased corticospinal excitability during AO and MI conditions may be attributed to corticospinal excitability being measured from the primary motor cortex. While AO, MI and AO+MI activate the primary motor cortex, a review of functional imaging studies (Hardwick and colleagues 2020) identified AO and MI to elicit a response of distinct neural regions that are unique to each modality (Figure 15). For example, a distinct cluster of neural regions have been identified to be active during AO including the ventral and dorsal premotor cortex and visual temporal and posterior parietal regions of the somatosensory cortex, while MI consistently recruits most premotor regions, including bi-lateral SMA, as well as parietal regions, such as the inferior and superior parietal lobe.

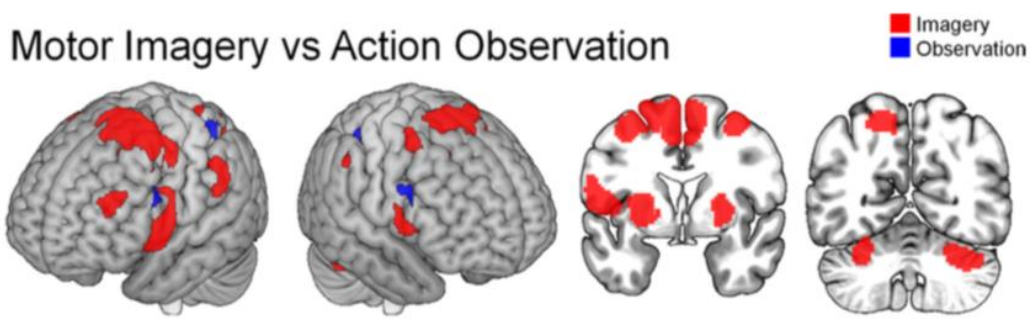


Figure 15. Contrast analysis showing activation patterns that are distinct to MI and AO via conjunction analysis of 303 neuroimaging studies. Adapted from Hardwick et al., 2018.

It is evident that due to the nature of AO being largely external, AO relies on a large range of processes outside of MI, such as external sensory processing and perception necessary for recognition, understanding (Rizzolatti & Sinigaglia 2010) and predicting actions (Springer et al., 2013). While the nature of MI involves more recruitment of cognitive-driven regions, such as prefrontal areas, and motor-driven regions like the cerebellum, in order to form an internal motor representation. By measuring change in excitability from the primary motor cortex, increased activity in areas outside of the primary motor cortex that may contribute to increased performance outcomes is missing; this is discussed in detail below.

The secondary purpose of this review was to identify methodological factors that may influence corticospinal excitability. Nine of the 21 studies included prior exposure to the imagery and/or observation task either via PP or modality specific practice (Table 2). Prior exposure did not have an effect on corticospinal excitability across studies, as an equivalent number of studies without prior exposure also found a significant effect of modality on excitability. It would be unlikely for prior exposure to significantly skew the results of the present review as all involved a single session. Therefore, no cumulative effect of physical practice could occur. Additionally, time engaged in task familiarization, in comparison to the amount of time engaged in group-specific modality is a relatively small exposure and was unlikely to have a substantial effect.

MI, AO and AO+MI of simple and complex movement tasks were seen to have an effect on corticospinal excitability. Interestingly, simple movement tasks had a pronounced effect on excitability during AO+MI compared to complex movement tasks. While simple movements such as finger abduction and adduction consist largely of activation of the first dorsal interosseous (FDI) muscle for movement to occur (particularly as most involved movement of the 2_{nd} digit), more complex movements, such as a reaching and grasping task, involve the recruitment of multiple muscle groups throughout the upper limb in order to execute. As small intrinsic hand muscles (like the FDI) are the predominant location from which MEPs are obtained, it is likely studies that implemented simple movements like finger abduction saw a larger increase in MEP amplitude during task compared to rest because the muscle from which they were obtaining the MEPs was the primary agonist, and as such the corresponding representation in the brain would be most excited. Additionally, the simultaneous nature of AO+MI relies on increased recruitment of neural resources (perceptual and cognitive mechanisms) resulting in increased cognitive load. It is likely when participants are required to engage in a complex movement via AO+MI compared to a simple movement, it is likely easier for participants to focus on the simultaneous observation and imagery of a simple movement and the kinesthetic sensation of a single muscle group compared to a movement that involves additional cognitive factors (e.g. observing a movement that is goal directed) while imagining the activation of multiple muscle groups.

As previously mentioned, MI and AO exist on a continuum from motor simulation to sensory resonance, respectively. Motor learning via MI is accomplished through a top-down process, through an internal cognitively driven representation of movement, while AO is largely an unconscious bottom-up process, formed through perceptual processes that rely on external information. By combining the cognitive nature of MI with the perceptual nature of AO, under the dual action simulation hypothesis, AO+MI should elicit a response from the brain creating an environment that is conducive to motor learning. Therefore, MI+AO should result in a greater effect on neural areas involved in motor learning and the production of movement than either modality alone. While the present review highlights AO+MI does result in increased corticospinal excitability compared to rest, the increased excitability in the primary motor cortex during AO+MI is comparable to changes in excitability seen during AO or MI independently. For example Meers and colleagues reported a significant effect of AO+MI of a finger flexion task on increased corticospinal excitability (MEP task – MEP rest = .81), however, Aoyama and colleagues had participants perform MI of the same task (finger flexion) and reported a change in corticospinal excitability comparable to Meers and colleagues findings (MEP task – MEP rest= .90; Aoyoma et al., 2019; Meers et al., 2020A). These findings hold true across the AO+MI studies included in the present review (Aoyoma et al., 2016; Cengiz et al. 2016A). A commonality amongst all studies included in the present review, as well as the majority of studies investigating neurophysiological changes during AO+MI is the use of TMS to stimulate the primary motor cortex. While previous studies have shown the primary motor cortex to be involved in AO and MI, Hardwick and colleagues have also highlighted brain regions outside of the primary motor cortex that are active during AO and MI. By measuring change in excitability, there is an assumption an increase in the excitability of the primary motor cortex is necessary in order for enhanced performance outcomes to be realized. However, the present review highlights that this may not be the case and increased excitation of neural regions outside of the primary motor cortex may be responsible for the resulting increase in subsequent physical performance. Thus, the present modality, TMS, used commonly among studies comparing AO+MI to AO or MI may not be the ideal modality for investigating the underlying changes in the brain that lead to increased performance. It may prove to be more advantageous to employ functional neuroimaging techniques (e.g., fMRI) in order to investigate changes in activation of areas outside of the primary motor cortex that may contribute to enhanced performance outcomes resulting from AO+MI.

The findings of the present review lead to the question of whether participants are able to perform AO and MI simultaneously, as suggested by the dual action simulation hypothesis, resulting in an additive effect of each modality. While studies have shown learning via AO+MI results in enhanced performance outcomes compared to either modality independently, it is not possible to evaluate the extent to which AO or MI is contributing to subsequent performance. It is plausible that one modality may drive changes in excitability, which lead to enhanced performance, while the other modality provides a favourable condition for learning (e.g. MI of a basketball free-throw enhanced through activation of mirror neurons during the observation of a basketball free-throw). While current literature is unable to parse out the role of each modality when applied simultaneously, future studies employing neuroimaging may be able to further investigate the role of each modality during AO+MI by investigating neural regions that are active during AO+MI, and comparing these areas to areas that are known to be exclusively active during one modality but not the other.

6.2 Limitations

While the present review controlled for extraneous variables included across studies, (e.g. social context, emotional components to stimuli etc.) through the three-phase screening process, the resulting articles included in the review do consist of various methodological differences. Prior research has shown methodological factors such as type of imagery or session length have an effect on MEP amplitude (Eaves et al., 2016; Lee et al., 2020). Ideally, in the present review the relationship between these variables, known to influence MEP amplitude, would have been identified, graphed and their impact interpreted. However, due to a lack of these variables being reported in the respective methods sections, including modality perspective and instruction, length and number of blocks when participants are engaged in the task via imagery or observation modalities, does not allow for investigating the relationship these factors may have on corticospinal excitability. For instance, the impact of task: rest ratio was recently demonstrated by Lee and colleagues, who showed that the duration of the blocks in which MI is performed has an effect on corticospinal excitability (Lee at al., 2020; Figure 16).

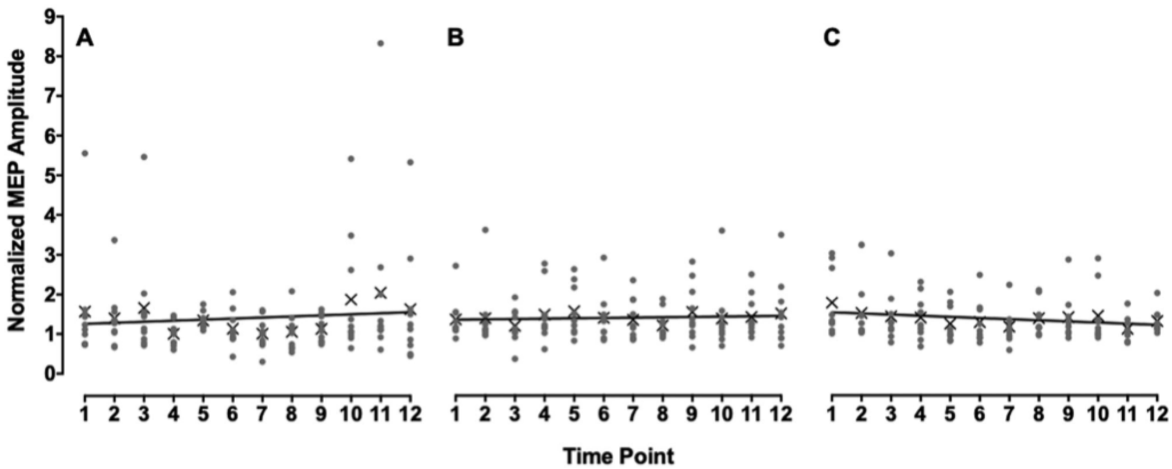


Figure 16. Normalized MEP values across timepoints for MI groups of 2, 4, and 6 minutes of imagery, graphs A, B and C, respectively. An increase in corticospinal excitability is seen across timepoints for the 2- and 4-minute conditions but not the 6-minute condition. Adapted from Lee et al., 2020.

The number of studies included were limited due to the reporting of results in the original studies being largely limited to statistical values. Few studies reported raw (or even averaged) MEP amplitude values (voltages) for task/rest (baseline) or included percentages resulting from normalizing MEP amplitude values during task to rest (or baseline). As such, there were fewer studies that included values which could be standardized, and in-turn quantified in order to compare across groups and studies. As a result, the present review included a minimal number of studies that included an AO+MI group, making it difficult to identify trends in data across studies that account for increased excitability seen across the four included AO+MI groups. While our screening strategy was developed in order to better control for the parameters around the studies included, we did not include incongruent AO+MI. Due to this, we may be missing data that could reveal whether one modality or the other (MI or AO) is responsible for driving changes in excitability by comparing incongruent AO+MI to congruent AO+MI.

6.3 Conclusion

The present review found AO, MI and AO+MI resulted in increased corticospinal excitability across conditions compared to rest. Task complexity was found to not have an effect on increased excitability; however, it is notable that for simple tasks AO+MI seemed to result in a pronounced effect compared to the increased excitability during AO+MI of complex tasks. Methodological factors such as task, instruction type, and length of session were unable to be fully considered as factors that may have influenced the findings of the present review due to lack of reporting in the studies included herein. While the present review revealed an overall trend of increased corticospinal excitability during AO, MI, and AO+MI, the increase in excitability was comparable across modalities, suggesting the increase in excitability of the primary motor cortex may not be responsible for increased performance, suggesting other neural regions involved in AO and MI may be driving the changes in performance.

6.4 Recommendations and Considerations

While the present review poses limitations on the conclusions that can be drawn, it identifies key areas of interest in imagery and observation literature as well as gaps and directions for future literature. It is evident that future studies should include detailed reporting of parameters, as prior work has shown variables such as imagery type and length of session influence corticospinal excitability. Moreover, it is important to explicitly state imagery instruction and perspective in order for conclusions to be drawn regarding the effect these variables have and to develop a standardized protocol for employing MI, AO and AO+MI. Additionally, the present review has highlighted gaps in AO+MI literature, including the need for studies to include both complex and simple task in order to better understand the effect task complexity has on corticospinal excitability during AO+MI compared to AO or MI.

Although there is a growing body of literature investigating the effect of AO+MI on behavioural outcomes and neurophysiological measures, to date, studies have investigated these measures separately. Future research should focus on including both behavioural and neurophysiological outcome measures in order to simultaneously investigate the neurophysiological processes underlying the enhanced behavioural outcomes previous studies have shown when AO and MI are applied simultaneously and compare these finding to AO and MI only training groups. Additionally, it would be beneficial for research to focus on understanding the change in activity during AO+MI compared to AO or MI of areas beyond the primary motor cortex that contribute to the subsequent increased performance outcomes in order to better understand the neurophysiological factors responsible for increased performance during AO+MI.

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APPENDIX A: Database Search Entries

Embase search history:

Search Number	Query	Results
#14	11 AND 12	519
#13	1 OR 2 OR 3 OR 4	15091
#12	5 OR 6 OR 7 OR 8 OR 9 OR 10 OR 11	7928
#11	'visual imagery'/exp OR 'visual imagery':ti,ab,kw	1419
#10	'action observation':ti,ab,kw OR 'motor imagery':ti,ab,kw	4939
#9	'kinesthetic imagery':ti,ab,kw	81
#8	'mental imagery'/exp	59
#7	'mental imagery':ti,ab,kw	2061
#6	'motor imagery'/exp OR 'motor imagery training'/exp	467
#5	'action observation'/exp	69
#4	'corticomotor excitability':ti,ab,kw	428
#3	'cortico excitability':ti,ab,kw	2
#2	'motor evoked potential'/exp OR 'motor evoked potential':ti,ab,kw	14386
#1	'corticospinal excitability'/exp OR 'corticospinal excitability':ti,ab,kw	1625
	Uploaded to Covidence 489 (30 duplicates removed)	

Medline search history:

Search Number	Query	Results
1	cortical excitability/ or evoked potentials, motor/	9411
2	("cortico excitability" or "motor evoked potential" or "corticospinal excitability" or "corticomotor excitability").ti,ab,kw,kf.	3854
3	1 or 2	10862
4	Imagery, Psychotherapy/	1797
5	((mental or motor or visual or kinesthetic) adj2 imagery).ti,ab,kw,kf.	5391
6	"action observation".ti,ab,kw,kf.	1302
7	4 or 5 or 6	7728
8	3 and 7	518

	Uploaded to Covidence 183 (335 duplicates removed)	

CINAHL Search history:

Search Number	Query	Results
S8	S3 AND S7	66
S7	S4 OR S5 OR S6	4,469
S6	TI action observation OR AB action observation	527
S5	TI ((mental or motor or visual or kinesthetic) N2 imagery) OR AB ((mental or motor or visual or kinesthetic) N2 imagery)	1,472
S4	(MH "Guided Imagery")	3,087
S3	S1 OR S2	2,600
S2	TI (corticospinal excitability OR cortico excitability OR motor evoked potential OR corticomotor excitability) OR AB (corticospinal excitability OR cortico excitability OR motor evoked potential OR corticomotor excitability)	1,381
S1	(MH "Evoked Potentials, Motor")	2,055
	Uploaded to Covidence 16 (50 duplicates removed)	

SPORTDiscus search history:

Search Number	**Query**	**Results**
S8	S6 AND S7	35
S7	S2 OR S3 OR S5	1,547
S6	S1 OR S4	2,197
S5	DE "IMAGERY (Psychology)" OR DE "MOTOR imagery (Cognition)"	576
S4	DE "EVOKED potentials (Electrophysiology)"	1,840
S3	TI action observation OR AB action observation	222
S2	TI ((mental or motor or visual or kinesthetic) N2 imagery) OR AB ((mental or motor or visual or kinesthetic) N2 imagery)	983
S1	TI (corticospinal excitability OR cortico excitability OR motor evoked potential OR corticomotor excitability) OR AB (corticospinal excitability OR cortico excitability OR motor evoked potential OR corticomotor excitability)	540
	Uploaded to Covidence 17 (18 duplicates removed)	

Appendix B: Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) Checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	Click here to enter text.
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	Click here to enter text.
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	Click here to enter text.
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	Click here to enter text.
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	Click here to enter text.
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	Click here to enter text.
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	Click here to enter text.
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	Click here to enter text.
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	Click here to enter text.
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	Click here to enter text.
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	Click here to enter text.

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	Click here to enter text.
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	Click here to enter text.
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	Click here to enter text.
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	Click here to enter text.
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	Click here to enter text.
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	Click here to enter text.
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	Click here to enter text.
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	Click here to enter text.
Limitations	20	Discuss the limitations of the scoping review process.	Click here to enter text.
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	Click here to enter text.
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	Click here to enter text.

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.

* Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote). ‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting. § The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

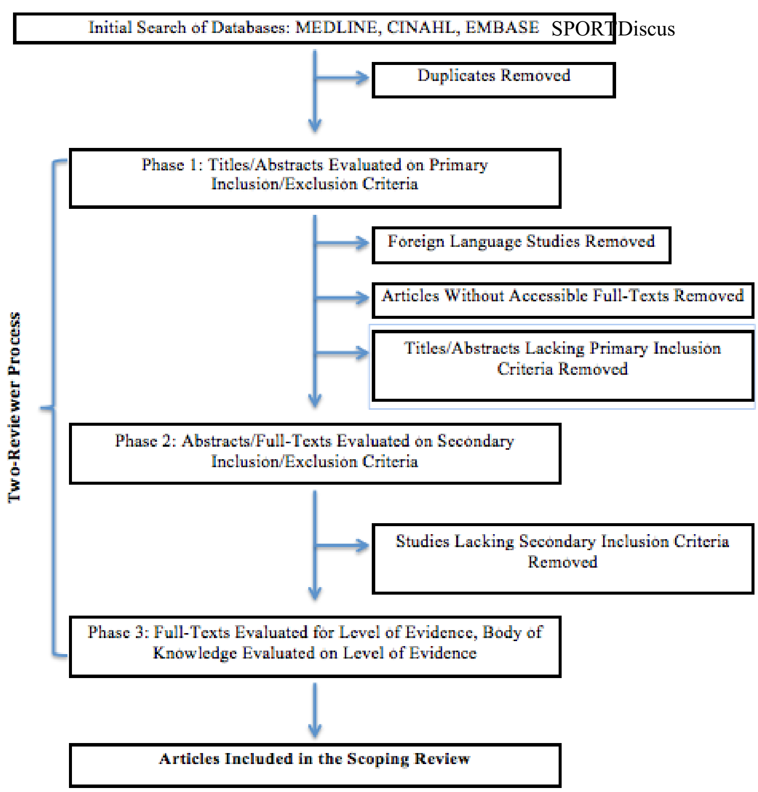
Appendix C: Inclusion/ Exclusion Criteria and Screening Procedure

Phase 1:

Inclusion Criteria	Exclusion Criteria
Healthy population	Clinical Population
Adult participants (18 and older)	AO, MI or AO+MI not applied to motor-related task
AO, MI, and/or AO+MI applied to motor-related task	Article in Foreign Language
TMS or measure of corticospinal excitability present	Article Inaccessible

Phase 2:

Inclusion Criteria	Exclusion Criteria
Task is upper limb focused	Motor task not focused on upper limb
AO or MI matches goal of movement	AO or MI does not match goal of movement
AO+MI is congruent	TMS not used to measure excitability
	Does not clearly quantify or report measure of corticospinal excitability
	AO+MI is incongruent



Appendix D: Data Extraction templates

Covidence #	Author	Year	Mean Age	Sex (#F/ #M)	Handedness	MI ability	Prior exposure to task (Y/N)

Covidence #	Modality type (AO)	Task Type	Session Length	Total Length	Instruction Delivery

Covidence #	MEP data (rest)	MEP data (task)	Location of electrode

Appendix E: Critical Appraisal Skills Programme Checklist

CASP
Critical Appraisal Skills Programme

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CASP Checklist: 10 questions to help you make sense of a Systematic Review

How to use this appraisal tool: Three broad issues need to be considered when appraising a systematic review study:

- Are the results of the study valid? (Section A)
- What are the results? (Section B)
- Will the results help locally? (Section C)

The 10 questions on the following pages are designed to help you think about these issues systematically. The first two questions are screening questions and can be answered quickly. If the answer to both is "yes", it is worth proceeding with the remaining questions. There is some degree of overlap between the questions, you are asked to record a "yes", "no" or "can't tell" to most of the questions. A number of italicised prompts are given after each question. These are designed to remind you why the question is important. Record your reasons for your answers in the spaces provided.

About: These checklists were designed to be used as educational pedagogic tools, as part of a workshop setting, therefore we do not suggest a scoring system. The core CASP checklists (randomised controlled trial & systematic review) were based on JAMA 'Users' guides to the medical literature 1994 (adapted from Guyatt GH, Sackett DL, and Cook DJ), and piloted with health care practitioners.

For each new checklist, a group of experts were assembled to develop and pilot the checklist and the workshop format with which it would be used. Over the years overall adjustments have been made to the format, but a recent survey of checklist users reiterated that the basic format continues to be useful and appropriate.

Referencing: we recommend using the Harvard style citation, i.e.: *Critical Appraisal Skills Programme (2018). CASP (insert name of checklist i.e. Systematic Review) Checklist. [online] Available at: URL. Accessed: Date Accessed.*

CASP
Critical Appraisal
Skills Programme

Paper for appraisal and reference:...

Section A: Are the results of the review valid?

1. Did the review address a clearly focused question?	Yes	☐	HINT: An issue can be 'focused' In terms of • the population studied • the intervention given • the outcome considered
	Can't Tell	☐	
	No	☐	

Comments:

2. Did the authors look for the right type of papers?	Yes	☐	HINT: 'The best sort of studies' would • address the review's question • have an appropriate study design (usually RCTs for papers evaluating interventions)
	Can't Tell	☐	
	No	☐	

Comments:

Is it worth continuing?

3. Do you think all the important, relevant studies were included?	Yes	☐	HINT: Look for • which bibliographic databases were used • follow up from reference lists • personal contact with experts • unpublished as well as published studies • non-English language studies
	Can't Tell	☐	
	No	☐	

Comments:

CASP
Critical Appraisal
Skills Programme

4. Did the review's authors do enough to assess quality of the included studies?

Yes ☐
Can't Tell ☐
No ☐

HINT: The authors need to consider the rigour of the studies they have identified. Lack of rigour may affect the studies' results ("All that glisters is not gold" Merchant of Venice – Act II Scene 7)

Comments:

5. If the results of the review have been combined, was it reasonable to do so?

Yes ☐
Can't Tell ☐
No ☐

HINT: Consider whether
- results were similar from study to study
- results of all the included studies are clearly displayed
- results of different studies are similar
- reasons for any variations in results are discussed

Comments:

Section B: What are the results?

6. What are the overall results of the review?

HINT: Consider
- If you are clear about the review's 'bottom line' results
- what these are (numerically if appropriate)
- how were the results expressed (NNT, odds ratio etc.)

Comments:

7. How precise are the results?

HINT: Look at the confidence intervals, if given

Comments:

Section C: Will the results help locally?

8. Can the results be applied to the local population?

Yes ☐ Can't Tell ☐ No ☐

HINT: Consider whether
- the patients covered by the review could be sufficiently different to your population to cause concern
- your local setting is likely to differ much from that of the review

Comments:

9. Were all important outcomes considered?

Yes ☐ Can't Tell ☐ No ☐

HINT: Consider whether
- there is other information you would like to have seen

Comments:

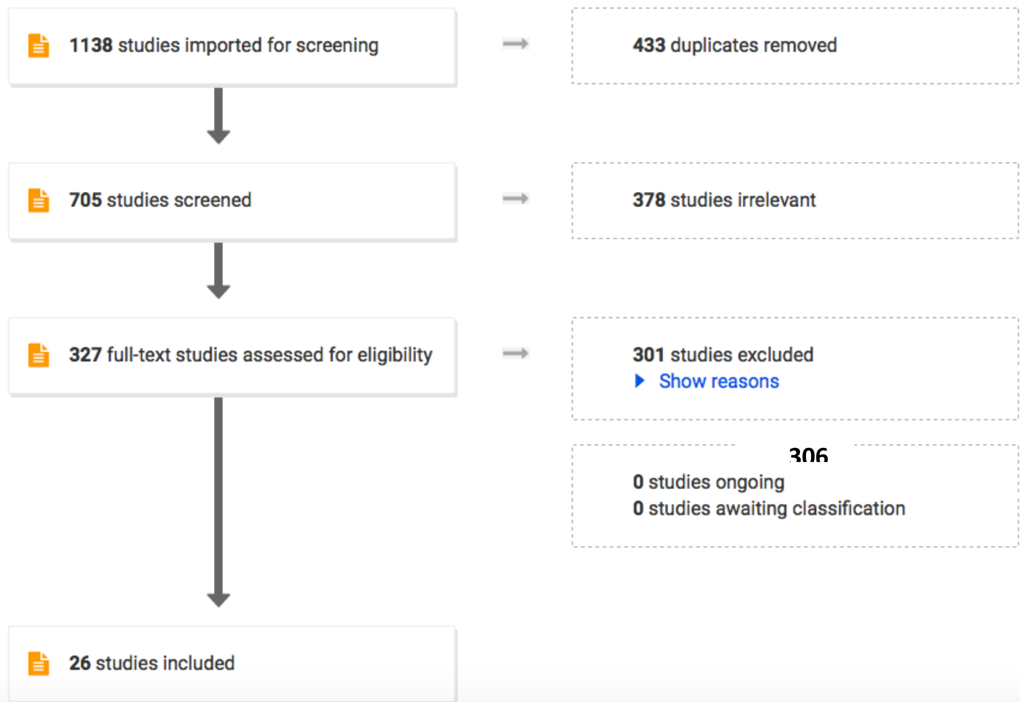
10. Are the benefits worth the harms and costs?

Yes ☐ Can't Tell ☐ No ☐

HINT: Consider
- even if this is not addressed by the review, what do you think?

Comments:

Appendix F: PRISMA Diagram



301 studies excluded

▼ Hide reasons

21 ental manipulation of task

Other (article not accessible, not English, abstract only, etc.)

60 Results not reported as voltage or %MEP

22 motor-related task is NOT upper limb focused

17 Does NOT clearly quantify or report measure of excitability (MEP amp. SR curve, cortical silent period) for AO, MI or AO+MI

16 between group design (except for AO, MI, AO+MI)

12 TMS is NOT used to measure cortical spinal excitability

11 AO, MI or AO+MI is NOT applied to motor task

3 AO or MI is NOT congruent with goal of movement

2 AO+MI is NOT congruent (watching foot tapping while imagery of finger tapping)