Motor Imagery: Does Strategy Matter?

By

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A thesis submitted to the School of Rehabilitation Therapy
in conformity with the requirements for the degree of Master of Science

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Kingston, Ontario Canada
August 2008

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Abstract

Motor imagery requires individuals to form an internal representation of a specific action within working memory without any overt output. Motor imagery has proven effective in improving motor performance of specific skills. This study explored whether different motor imagery strategies influence corticospinal excitability in young (20-35 years) and older subjects (over 55 years). In addition, the effectiveness of these strategies in targeting modulations in motor cortical output and whether the hand “performing” the task was important were also examined. Motor imagery ability was measured using the Kinesthetic and Visual Imagery Questionnaire (KVIQ) and mental chronometry. Working memory including visuospatial, verbal and kinesthetic domains was measured by immediate serial recall. To determine the effect of imagery on corticospinal excitability transcranial magnetic stimulation (TMS) was applied over the contralateral motor cortex as subjects imagined abducting their index finger. Motor evoked potentials (MEPs) were recorded from first dorsal interosseous (FDI), abductor pollicis brevis and abductor digiti minimi muscles (ADM). As subjects performed motor imagery, they were guided by visual, auditory or a combination of visual and auditory cues. Strategies were introduced in randomized sequence interspersed with a rest and a muscle activation condition. Motor imagery ability and verbal working memory were comparable between young and older subjects (p > 0.05). In both groups, MEP amplitudes in the FDI muscle were significantly increased during motor imagery compared to rest regardless of the strategy used (p < 0.001). Visual cueing was the most effective at isolating facilitation to the target muscle (FDI), whereas with the auditory and combined strategies both FDI and ADM muscles generated MEPs that were comparable in amplitude (p > 0.05). TMS induced MEPs were greater in amplitude when the left hemisphere was stimulated during motor imagery of
the right finger while being guided by either auditory or visual cueing. In combination, these findings suggest that motor imagery increases corticospinal excitability and the strategy used may serve to target the facilitation.
Acknowledgements

I would like to extend my sincerest thank you to everyone who participated in this study. For all the assistance from Tatianna Wu, thank you, this would not have been the same without your time and dedication.

Sincere appreciation is extended to Dr. Brenda Brouwer for her endurance, honesty and dedication. It was an honour and privilege to have had her as a supervisor and to have witnessed her devotion to academia.

To my family, thank you for all the “mileage” you put into this and to the warm welcome upon each of my returns. To the Catino family, thank for your support, the abundance of food you sent through “courier” and for providing a study space with, obviously, food included. To my friends, thank you for your encouragement, your visits, loving emails and phone calls, and your understanding for my “temporary leave of absence” from all the moments I missed these past 2 years.

To my fiancé, Anthony, your infinite support, guidance, understanding, affection and encouragement has humbled me beyond words. Thank you for all the late night laughs! Thank you for instilling in me the belief that I am capable of achieving anything I put my mind to – for once I will give you credit that you were right! Thank you for constantly reminding me that “you measure the size of your accomplishments by the obstacles you had to overcome to reach your goals”. With you by my side I have no doubt that I can conquer the world. Sono tanto benedetto di ti avere nella mia vita. Grazie.
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<tr>
<td>ADM</td>
<td>Abductor Digiti Minimi</td>
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<td>ANOVA</td>
<td>Analysis of Variance</td>
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<td>APB</td>
<td>Abductor Pollicis Brevis</td>
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<td>EMG</td>
<td>Electromyography</td>
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<td>FDS</td>
<td>Flexor Digitorum Superficialis</td>
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<td>FDI</td>
<td>First Dorsal Interosseous</td>
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<td>fMRI</td>
<td>Functional Magnetic Resonance Imaging</td>
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<td>ICI</td>
<td>Intracortical Inhibition</td>
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<td>KVIQ</td>
<td>Kinesthetic and Visual Imagery Questionnaire</td>
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<td>M1</td>
<td>Primary Motor Cortex</td>
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<td>MEP</td>
<td>Motor Evoked Potentials</td>
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<td>MNS</td>
<td>Mirror Neuron System</td>
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<td>MT</td>
<td>Motor Threshold</td>
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<td>NMR</td>
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<td>SMA</td>
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Chapter 1: Introduction

Mental practice has been used by athletes for over 50 years to help promote motor learning when physical practice is not possible (Malouin et al. 2004). More recently, investigators have proposed that mental practice using motor imagery may be an effective rehabilitation tool in neurological rehabilitation (Sharma, Pomeroy & Baron 2006). Motor imagery is an active cognitive process during which the representation of a specific action is internally reproduced within working memory without any overt motor output (Decety, Grezes 1999). Motor imagery on its own has not always proven to be effective (Driskell, Copper & Moran 1994), however, in combination with physical practice, it has been shown to be more effective than physical practice alone (Brouziyine, Molinaro 2005, Page et al. 2001a).

Motor imagery appears to share phenomenological aspects with movement execution, which has been supported by several findings. Behavioural studies have revealed improvements in motor performance (Driskell, Copper & Moran 1994) and increases in muscle strength in association with motor imagery (Yue, Cole 1992). Vegetative parameters such as heart rate, blood pressure and breathing frequency have been shown to increase proportionally to the physical challenge imagined during motor imagery (Decety et al. 1991). Neurological studies have consistently shown activation of similar cortical areas during motor execution and motor imagery such as the primary motor cortex (M1) (Hashimoto, Rothwell 1999), cingulate cortex (Lacourse et al. 2005) and parietal areas (Gerardin et al. 2000). Transcranial magnetic stimulation (TMS) studies have revealed an increase in corticospinal excitability during motor imagery when compared to a resting state (Rossini et al. 1999). Furthermore, neurological studies have
demonstrated that motor imagery can be used to acquire new skills (Lacourse et al. 2005, Lafleur et al. 2002).

In combination, these findings suggest that motor imagery can be of benefit to motor performance. The potential of motor imagery as a rehabilitation technique or a method for cognitive practice in athletes has been generally supported (Braun et al. 2006, Driskell, Copper & Moran 1994, Sharma, Pomeroy & Baron 2006), although some studies have failed to demonstrate its benefits (Liu et al. 2004, Stevens, Stoykov 2003). A challenge of motor imagery research is that the investigator cannot be sure what the person is mentally rehearsing (Malouin et al. 2008a, de Lange, Roelofs & Toni 2008b). In an attempt to standardize what subjects image researchers use audiotapes (Page et al. 2001a), metronomes (Binkofski et al. 2000, Lotze et al. 1999) and visual cues (Crosbie et al. 2004). What is not known is whether the strategy used to cue imagery is important in determining the effectiveness of motor imagery. This thesis will address this issue.
Chapter 2: Literature Review

BEHAVIOURAL EVIDENCE ASSOCIATED WITH MOTOR IMAGERY

Motor imagery is a type of mental imagery, which requires individuals to form an internal representation of a specific action within working memory without any overt output (Decety, Grezes 1999). Jeannerod (Jeannerod 1995b) stated that conscious motor imagery and unconscious motor preparation share common mechanisms that are functionally equivalent. An important aspect of motor imagery is that it allows one to investigate the internal dynamics of motor control, including motor planning and preparation (de Lange, Roelofs & Toni 2008a). Mental practice using motor imagery has been primarily used by athletes to improve motor skills (Driskell, Copper & Moran 1994). Studies in sport psychology have shown that mental practice using motor imagery improves performance compared to not having any practice, but less so than physical practice alone (Driskell, Copper & Moran 1994).

Motor imagery can be experienced from an external perspective (third person perspective) or an internal perspective (a person imagines themselves performing an action). Motor imagery can also involve either kinesthetic or visual representation. Kinesthetic motor imagery involves imagining the sensations associated with actual task performance, while visual motor imagery involves focusing on the clarity of seeing the movement in the mind’s eye (Stinear et al. 2006). Mental rehearsal requires that subjects maintain both visual and kinesthetic information in their working memory, or short-term memory (Malouin et al. 2004), hence impairments in working memory could negatively impact one’s imagery ability. Some studies have compared visual and kinesthetic imagery...
(Stinear et al. 2006) and imagery from first and third person perspective (Fourkas et al. 2006). When compared to visual motor imagery (e.g. imagining seeing your finger move), kinesthetic motor imagery (e.g. imagining the sensations associated with moving your finger) was shown to modulate corticospinal excitability to a greater extent than visual imagery (Stinear et al. 2006). Subjects were asked to imagine briskly tapping their thumb downwards at a pace of 1Hz under four conditions: rest (where they thought of nothing), visual static imagery (where they imagined looking at the outside of their house), visual motor imagery (where they imagined seeing their thumb moving in time with the metronome), and kinesthetic motor imagery (where they imagined the sensations associated with tapping their thumb in time with the metronome). Only kinesthetic motor imagery and not visual motor imagery was able to elicit larger motor evoked potentials (MEPs) than both rest and visual static imagery conditions. From a behavioural standpoint, there appears to be differences in the effectiveness of visual and kinesthetic imagery (Fery 2003). Fery (Fery 2003) compared kinesthetic and visual imagery in 25 male subjects who were instructed to reproduce the shape of a form with their finger. Subjects in the kinesthetic group had their hand passively moved by an evaluator to help them feel the sensations associated with the shape of the form (i.e. edges, curves, lines etc), while subjects in the visual group watched the evaluator draw the form. Subjects were then asked to practice the task using either kinesthetic or visual imagery as appropriate and to focus on timing as well. After imagery they drew the form as precisely as possible both in terms of shape and timing. Those who engaged in visual imagery showed better reproduction of the form’s shape, while those who performed kinesthetic imagery demonstrated more accurate temporal reproduction.
Several theories have been proposed to explain the mechanisms by which motor imagery improves actual physical performance. The two most prominent theories include the psychoneuromuscular and central representation theory. The psychoneuromuscular theory, also called the peripheral or ideomotor theory postulates that when a person performs mental practice muscles are activated in a pattern consistent with overt movement execution but subthreshold for visible movement (Boschker, Bakker & Rietberg 2000, Mulder et al. 2004). It is believed that mental practice facilitates learning by exercising the neural pathway thereby strengthening motor programs and priming the corresponding motorneurons of the muscles necessary to execute a motor task (Magill 2007, Mulder 2007, Page et al. 2001a). Early support for this theory dates back to 1932 when Jacobson (Jacobson 1932) demonstrated micronerve impulses propagated to the target muscles in the absence of overt movement when subjects imagined a performing a physical movement.

Central representation theory or the cognitive theory (Jeannerod 1995a) claims that actions are driven by internally represented goals. This theory postulates that improvements achieved by mental practice are due to higher levels of the motor system involved in motor planning and programming (Yue, Cole 1992). Although motor preparation is an unconscious process, it is assumed that it can be accessed consciously through motor imagery (Jeannerod 1995a). Functional magnetic resonance imaging (fMRI) has revealed that premotor areas and the supplementary motor areas (SMA) are activated during overt movement and motor imagery (Jeannerod 1995a), both areas have been shown to be involved in motor planning (Kandel, Schwartz & Jessell 2000).
In order to perform motor imagery effectively, one must be able to visualize a motor action within their mind, which in turn will activate the appropriate cortical areas involved in motor learning. Relatively little is known concerning the effects of aging and the ability to perform motor imagery. Mulder and colleagues (Mulder et al. 2007) addressed this question by comparing vividness of movement imagery scores between three age groups including young (under 30 years), intermediate (30-64 years), and older adults (over 64 years). The older adults preserved the ability to perform motor imagery, however, they performed significantly worse at first person imagery than the younger groups. Hence, although older adults maintain the ability to imagine a motor action, the benefits of motor imagery might decrease with age since first person imagery has been suggested to be more effective than third person imagery (Fourkas et al. 2006, Jackson et al. 2001). Using a chronometry paradigm, Molina et al. (Molina, Tijus & Jouen 2008) studied the emergence of motor imagery ability in childhood. A group of 40 children aged five, and a group of 40 children aged seven were asked to either physically walk or imagine walking towards a dollhouse with the goal of placing a puppet inside (standard situation). In addition, during one of the trials, children were told to pretend the puppet was heavy during both physical and imagined conditions (informed situation). Chronometric data revealed a significant correlation between imagined and physical walking tasks in both situations, only the seven year old children, indicating that at five years of age children are not able to explicitly imagine themselves perform an action, whereas at the age of seven the ability to perform motor imagery is acquired. The authors concluded that this difference in imagery ability might be related to the development of cognitive processes involved in motor representation which in turn is attributed to the development of prefrontal and parietal structures of the brain.
Whether or not people with neurological conditions can perform motor imagery has also been investigated (Malouin et al. 2008a, Tremblay, Leonard & Tremblay 2008). Malouin and colleagues (Malouin et al. 2008a) assessed whether motor imagery ability is preserved after a stroke whereas Tremblay et al. (Tremblay, Leonard & Tremblay 2008) evaluated a group of people with Parkinson’s disease to determine if their movement limitations would be reflected in their capability to perform motor imagery. Malouin and colleagues had their subject’s complete the Kinesthetic and Visual Imagery Questionnaire (KVIQ). Subjects rated their imagery ability in terms of the vividness of an image and the intensity of the sensations associated with the image they imagined. Results revealed that after a stroke, the ability to perform motor imagery is maintained since the KVIQ scores were similar to an age matched healthy group. The subjects in the stroke group, however, had better visual imagery abilities than kinesthetic abilities suggesting that it was easier to visualize the image in their mind than feel the sensations associated with the movement. In contrast, Tremblay and colleagues (Tremblay, Leonard & Tremblay 2008) demonstrated that the ability to engage the motor system in motor imagery actions is not preserved in subjects with Parkinson’s. Transcranial magnetic stimulation was applied to the motor cortex as subjects imagined cutting paper with scissors. Results revealed that when compared to healthy adults, people with Parkinson’s disease failed to exhibit facilitation of the first dorsal interosseous (FDI) muscle, which the authors attributed to limitations in movement preparation and action representation resulting from Parkinson’s. Alkadhi and colleagues (Alkadhi et al. 2005) explored motor imagery in spinal cord patients to determine whether the ability to activate neurons in the primary motor cortex is maintained. Both healthy subjects and spinal cord patients were asked to imagine executing repetitive foot flexion and extension while having an fMRI. Strong activation
of brain regions including M1 were evident in the spinal cord patients, and to a greater extent than the healthy group. This suggests that a motor representation in M1 is sufficient to perform motor imagery, the capacity for afferent feedback is not required. In summary, once cortical areas associated with motor imagery have been adequately developed by about the age of seven, one maintains the ability to perform motor imagery as long as the ability for motor planning is preserved.

Professional athletes strive to improve motor performance, thus studies have often assessed whether motor imagery can be used to improve motor skills. For instance, a recent study by Olsson and colleagues (Olsson, Jonsson & Nyberg 2008) examined whether motor imagery training would promote the improvement of performance in high jumpers. Subjects were placed in either a physical practice or a combined physical practice with motor imagery group. For a period of six weeks all subjects practiced jumping over a bar according to their respective group. Both groups had the same amount of physical practice however the combined group had an additional six minutes of motor imagery training at each session. Pre and post training intervention revealed significantly greater improvement in bar clearance in the motor imagery training resulted than the physical practice group. Pascual-Leone (Pascual-Leone et al. 1995) also demonstrated that it is possible to improve performance through motor imagery training. Eighteen subjects without musical experience were taught a one handed five finger exercise on the piano. Once they knew how to perform the motor task, they were randomly assigned to either a physical practice group, mental imagery group, or control group (no imagery or physical practice). After practicing two hours per day for five days both physical practice and motor imagery groups demonstrated improvements in the piano task. In addition,
compared to the control group, motor imagery training significantly increased the size of cortical output maps (measured via TMS) for the FDI muscle. On the other hand, although the physical performance group had greater improvements performing the skill, when the size of the cortical output maps were compared to the imagery group, no differences were seen, therefore indicating that motor imagery is strongly associated with motor learning and cortical reorganization affiliated with motor learning. Olsson et al. (Olsson, Jonsson & Nyberg 2008) and Pascual-Leone (Pascual-Leone et al. 1995) illustrate the diversity of motor imagery at improving motor performance of a task that was either already known as well as more complex (i.e. high jumpers) versus a novel and more simplistic task.

Motor imagery has been used as a strategy to increase muscle strength (Yue, Cole 1992). After five sessions per week (for four weeks) of motor imagery or physical training involving maximal abductor digiti minimi (ADM) contractors, the maximal isometric force generated by the hypothenar muscles increased by 22% and 30%, respectively compared to 3.7% in those who did not train (Yue, Cole 1992). Ranganathan et al. (Ranganathan et al. 2004) supported these findings showing that motor imagery improved muscle strength compared to no practice at all. Thirty young, right handed individuals with no previous training experience were randomly assigned to either mental practice of finger abduction (5th digit), or elbow flexion. Abductor digiti mini strength from these groups were compared to a control group who did not practice at all and another that engaged in physical practice alone. After 12 weeks of training, (five times per week, 15 minutes per each session), those who mentally practiced finger abduction demonstrated larger increases in ADM strength (35%) compared to those who “practiced”
elbow flexion (13.5 %). No strength improvements were seen in the control group and significant increases in strength were seen in the physical practice group (53%) demonstrating that mental practice using motor imagery can improve muscle strength, albeit the improvements are not as large as physical practice alone.

In rehabilitation, it can be difficult to perform exercises with a hemiparetic upper limb and limited voluntary movement. If motor imagery can promote physical recovery by enhancing neuromotor connections then those with severe impairments may benefit. Several studies have demonstrated the effectiveness of motor imagery at improving upper limb function (Crosbie et al. 2004, Liu et al. 2004, Page 2001, Page, Levine & Leonard 2005, Page, Levine & Leonard 2007), improving gait performance (Dickstein, Dusky & Marcovitz 2004, Dunsky et al. 2006), and restoring abnormalities in the brains motor system function after a complete spinal cord injury (Alkadhi et al. 2005, Cramer et al. 2007). Page and colleagues have consistently shown that motor imagery is effective in stroke rehabilitation as an adjunct to physical practice. In one of their studies, stroke patients were divided into a physical practice group or combined motor imagery and physical practice group (Page et al. 2001a). All subjects received three sessions of physical therapy per week lasting one hour, whereas the combined group had an additional 10 minutes of imagery five times per week. Subjects in the physical training group remained at the same functional levels after six weeks, whereas the combined therapy group significantly improved their functional ability which was assessed by the Fugl-Myer Assessment of Motor Recovery and the Action Research Arm Test. Dunsky and colleagues (Dusky et al. 2006), on the other hand, investigated the effects of motor imagery on gait in persons with chronic hemiparesis. After imagining themselves walking
at their own pace (three times a week for six weeks), subjects improved their gait speed, decreased double limb support and increased stride length.

In combination, these findings support the benefits of motor imagery in many populations as a means of promoting motor learning and improving motor skills.

NEUROLOGICAL EVIDENCE ASSOCIATED WITH MOTOR IMAGERY

Studies have shown that similar cortical areas are activated during movement execution and motor imagery including premotor areas, the parietal lobule, basal ganglia, anterior cingulate cortex and the cerebellum (Dechent, Merboldt & Frahm 2004, Gerardin et al. 2000, Grezes, Decety 2001, Hanakawa et al. 2003, Lacourse et al. 2005, Lotze et al. 1999). Understanding the role of these areas in terms of executing skilled voluntary movements helps with the understanding of the fundamentals of motor imagery. The cerebellum, for instance, has a major role in planning and in the organization of multisegment movement and is also involved in verbal working memory (Oliveri et al. 2007). When performing motor imagery neurons in the SMA, premotor cortex, and parietal areas have been shown to be consistently activated (Gerardin et al. 2000, Kuhtz-Buschbeck et al. 2003, Lacourse et al. 2005, Lacourse et al. 2005, Lotze et al. 1999, Stephan et al. 1995). These areas are particularly interesting due to their involvement in movement preparation and planning (Decety 1996, Lotze, Halsband 2006).

Whether M1 is activated during motor imagery is inconclusive due to conflicting results. In an fMRI study, six young, healthy volunteers executed sequential finger-to-
thumb opposition movements which were associated with the activation of several
cortical areas (Dechent, Merboldt & Frahm 2004). Although the SMA and premotor areas
were activated during motor imagery, results failed to show activation of M1. Gerardin et
al. (Gerardin et al. 2000) similarly reported that M1 was silent during imagery of finger
flexion and extension during fMRI. However, other imaging studies have seen M1
activation during motor imagery (Kuhtz-Buschbeck et al. 2003, Lotze et al. 1999, Porro et
al. 1996). For instance, results from an fMRI study by Lotze and colleagues (Lotze et al.
1999) showed that compared to the physical execution of making a fist with the hand,
imagining this task activates similar areas including the M1, albeit to a lesser extent.

Transcranial magnetic stimulation has proven to be a valuable tool to explore
modulation of corticospinal excitability during motor imagery (Abbruzzese et al. 1999,
1999, Yahagi, Kasai 1998, Yahagi, Kasai 1999). TMS is a painless, non-invasive method
that produces parallel currents when applied overlying the motor cortical region. TMS
activates corticospinal neurons transynaptically through cortical afferents which project
onto corticomotoneurons therefore providing a means of exploring the excitability of the
motor cortex (Day et al. 1987). TMS induced MEPs have been shown to increase in
amplitude during motor imagery similar to when muscles are voluntarily activated
(Fadiga et al. 1999, Kasai et al. 1997, Kuhtz-Buschbeck et al. 2003, Rossini et al. 1999,
Stinear, Byblow 2003a, Yahagi, Kasai 1999). In contrast, following transcranial electrical
stimulation (TES), modulation of corticospinal excitability has not been observed during
motor imagery (Pascual-Leone et al. 1998). Unlike TMS, electrical currents induced by
TES flow perpendicular to the surface of the skull which preferentially activate cortical
motor neurons directly at the axon hillock (Branston, Tofts 1990, Day et al. 1987). The different responses generated from TMS and TES during motor imagery provide insight regarding excitability of cortical motor neurons. It suggests that modulation of cortical motor output during motor imagery results from activation of afferent projections onto the M1 originating from premotor regions.

Voluntary movement of different actions, for instance, simple versus complex hand movements, have been shown to have differential effects on cortical activation, such that the strength of activation and cortical regions activated differ (Cui et al. 2000, Rao et al. 1993). Whether this also occurs during imagined tasks has been explored by Kuhtz-Buschbeck and colleagues (Kuhtz-Buschbeck et al. 2003). Using TMS and fMRI, Kuhtz-Buschbeck demonstrated that motor imagery of a complex task differentially modulates corticospinal excitability as compared to a simple motor task. For instance, as a simple task subjects squeezed a foam block between their thumb, index and middle finger, whereas the complex task involved a finger-tapping sequence where each finger was tapped by opposing the thumb (the number of taps being different for each finger). When compared to a resting condition, TMS data revealed larger increases in MEP amplitude during the complex task compared to the simple task. fMRI data demonstrated commonalities in areas activated (SMA and dorsal and ventral premotor areas) during complex or simple motor tasks, however, the complex task was attributed to stronger activation of these areas. M1 was also activated more strongly during imagery of the complex task, according to the fMRI. Hence, it is clear that the task being imagined influences the degree in cortical areas activated.
It has often been questioned whether increases in corticospinal excitability seen during motor imagery occur exclusively at a cortical level. Kasai et al. (Kasai et al. 1997) had subjects imagine wrist flexion and extension movements during which, TMS was applied over the contralateral motor cortex to reflect cortical excitability and spinal excitability was measured by Hoffman reflex (H-reflex). The H-reflex is an electrically induced monosynaptic stretch reflex reflecting the integrity of Ia sensory fibers, the spinal motor neurons, and their efferent projections (Kandel, Schwartz & Jessell 2000). MEPs elicited in the flexor carpi radialis were shown to increase during motor imagery of wrist flexion while the H-reflex elicited by electrical stimulation of the median nerve did not change in amplitude. This indicates that during motor imagery cortical excitability is increased without any changes in spinal motoneuron excitability, supporting the notion that imagery is a supraspinal process (Hashimoto, Rothwell 1999, Kasai et al. 1997).

During voluntary movement, movement of a single finger can activate digit representations distributed throughout the hand area in M1 (Porter, Lemon 1993, Schieber, Hibbard 1993). This phenomenon is known as enslaving, caused by diverging projections from finger representations within M1 which project to adjacent finger representations (Latash et al. 2002). If the projection strength to adjacent representations is sufficient then the prime mover and other muscles in proximity may be activated. It is possible that an enslaving effect may also occur during motor imagery such that cortical facilitation may be non-specific, i.e. not isolated to a target muscle. Marconi and colleagues (Marconi et al. 2007) concluded that motor imagery of a task involving a single muscle enhances cortical excitivity to the target muscle and others that are not “involved” in the task. When subjects imagined thumb opposition towards the base of the
small finger (opponens pollicis being the target muscle), MEPs were facilitated in both opponens pollicis (OP) and FDI muscles. Fadiga and colleagues (Fadiga et al. 1999) also found that during motor imagery MEP amplitudes increase in both agonist and antagonist muscles. While subjects imagined opening and closing their right hand, TMS induced MEPs were recorded from OP, FDI and extensor digitorum communis muscles. While performing imagery of closing the hand, MEP amplitudes increased in both agonist (OP and FDI) and antagonist (extensor digitorum communis) muscles, this increase was shown to be more pronounced in the dominant hemisphere than the non-dominant. Stinear et al. (Stinear, Byblow 2004) however, assessed modulation of corticospinal excitability as subjects imagined applying downward pressure on a computer mouse using only their index finger. Electromyographic (EMG) data recorded from FDI and abductor pollicis brevis (APB) muscles of the dominant hand revealed larger MEPs elicited in the FDI muscle than in the APB muscle, compared to rest. Isolation of facilitory effects to the target muscle has been confirmed by several other studies (Facchini et al. 2002, Li 2007, Rossini et al. 1999). In combination these studies indicate a lack of consensus that may be attributed to several factors. Imagery ability has been shown to influence the effectiveness of motor imagery (Roure et al. 1999) but is not typically assessed. High imagery ability allows for a clearer representation of the task being imagined which could help isolate facilitory responses to the target muscle only.

In summary, research has indicated that the neural substrates of motor imagery are comparable to those of motor task execution. As a cortical process, motor imagery may be well suited to a wide range of subjects, even those with limited muscle function.
PHYSIOLOGICAL EVIDENCE ASSOCIATED WITH MOTOR IMAGERY

It has been well established that motor imagery induces autonomic responses such as elevated heart rate, blood pressure and respiration during imagined cardiovascular exercises (Decety et al. 1991), and specific sport skills (Oishi, Maeshima 2004, Roure et al. 1999). Heart and respiratory rates were assessed by Decety et al. (Decety et al. 1991) who investigated whether vegetative responses normally seen during cardiovascular training were replicated during motor imagery. A group of 11 healthy young subjects were instructed to imagine themselves running on a treadmill after having physically performed the task. Subjects wore earphones through which they heard the sounds of the treadmill belt moving at different speeds (comparable to speeds they had physically experienced) while respiration and heart rate were recorded. Both responses increased as a function of belt speed during imagery, although not to the same extent as occurred during actual physical performance. Muscle activity was not monitored, therefore it is possible that some activation occurred during motor imagery which would have an associated physiological response. Since no visible muscle activity was evident, however, it is unlikely that this could explain the findings. Decety and colleagues (Decety et al. 1993) used nuclear magnetic resonance (NMR) spectroscopy to measure muscle metabolism during physical performance and motor imagery. They confirmed that both heart rate and respiration increased during motor imagery in a manner consistent with what was observed during physical practice, though the magnitude was lower. These physiological responses occurred without any increases in muscle metabolism.
Autonomic responses have been shown to differentiate between people with poor and good imagery abilities (Guillot, Collet & Dittmar 2004, Oishi, Maeshima 2004, Roure et al. 1999). For instance, a recent study by Oishi et al. (Oishi, Maeshima 2004) investigated the autonomic responses during motor imagery in athletes. Since elite athletes have better imagery skills and can imagine a task more vividly, elite speed skaters were compared to non-elite speed skaters without imagery experience to determine whether imagery ability influenced autonomic responses. Subjects listened to an audiotape of sounds associated with a 500 meter speed skating race and imagined themselves competing in the race. This motor imagery task was compared to a highly stressful mental arithmetic task to enable researchers to distinguish the physiological effects related to stress (mental arithmetic) from those related to the motor task (motor imagery). In both groups, increases in respiratory rate and heart rate occurred during both motor imagery and mental arithmetic tasks to the same degree indicating that stress alone caused the increase. However, compared to the non-elite athletes, larger increases in respiration and heart rate were seen in the elite athletes during motor imagery. Roure et al. (Roure et al. 1999) explored this concept further by studying whether imagery ability could be estimated by autonomic responses and whether motor imagery training would improve performance. Twenty-four volleyball players underwent a volleyball skill pretest (based on the ability to accurately pass an opponent’s serve to a teammate) and completed an imagery ability test (Movement Imagery Questionnaire). All 24 players were divided into either an imagery or non-imagery group with an equal amount of “skilled” and “less-skilled” players and “high” and “low” imagers in each group. The non-imagers worked on a neutral task for two months which consisted of a 30 minute conversation with the experimentalist. The imagery group listened to an audiotape of volleyball serves and were
asked to imagine “seeing” and “feeling” themselves receiving the opponent’s “serve” and passing it to a “teammate” (same task performed during the pretest). Imagery training occurred three times per week for 30 minutes, for a total of two months. Autonomic responses were measured during the physical pretest, posttest and during the imagery group’s last training session. A total of six autonomic parameters were quantified including: skin potential, skin resistance, skin blood flow, skin temperature, instantaneous heart rate and respiration frequency. Results showed that the imagery group had greater performance improvements than the non-imagery group. Moreover, in the imagery group, those with higher imagery ability had greater performance improvements than the “poor” imagers. Performance improvements acquired through motor imagery were shown to be correlated with autonomic responses suggesting strong motor imagery ability increases access to neural circuits which in turn activate the appropriate autonomic response which may help improve performance.

On balance, it seems that practicing motor imagery or motor execution produces similar benefits in terms of motor learning and performance and there are commonalities in the neural behavioural and physiological responses between the 2 practice conditions. Variations in findings and conclusions from different studies may stem from the motor imagery strategies used. For example, in some studies auditory curing was used to guide motor imagery (ref) whereas others used visual cues (refs). It is not known whether different strategies are equally effective.
STRATEGIES USED IN MOTOR IMAGERY

Although many studies have shown that motor imagery can improve motor performance, it is difficult to assess how well a subject is performing motor imagery (de Lange, Roelofs & Toni 2008a) which can impact the benefit. Strategies used to help people focus during motor imagery include metronomes (Binkofski et al. 2000), verbal cues from the evaluator (Levin et al. 2004), pictures illustrated on computer screens to help subjects visualize the motor task (Leonard, Tremblay 2007), and auditory tapes to cue subjects to initiate imagery of the task (Page et al. 2001a, Page, Levine & Leonard 2007). Some studies do not use any strategy but simply assume the subjects are focusing and imagining the motor task (Kasai et al. 1997, Szameitat, Shen & Sterr 2007, Takahashi et al. 2005, Vargas et al. 2004).

The most commonly used strategy for motor imagery is auditory cueing. Page and colleagues provided subjects with an audiotape encouraging them to focus attention on the motor task (i.e. grabbing a coffee cup) to be imagined (Page et al. 2001a, Page et al. 2001b, Page, Levine & Leonard 2005, Page, Levine & Leonard 2007). Other researchers give verbal commands to cue subjects to mentally initiate imagining the motor task, which has also been successful at increasing corticospinal excitability (Cicinelli et al. 2006). Yue and Cole (Yue, Cole 1992) used verbal guidance instructing subjects to perform a maximal voluntary contraction for 15 seconds in their mind’s eye and provided encouragement (“harder”) throughout the duration of the “contraction” which resulted in an increase in muscle strength. Stinear et al. (Stinear, Fleming & Byblow 2006) compared MEP amplitudes recorded during motor imagery with an auditory cue and with no cue. Results demonstrated greater cortical excitability with cueing especially when subjects
performed kinesthetic motor imagery. In contrast, Crews and Kamen (Crews, Kamen 2006) did not find any benefit of auditory cueing. All subjects initial training before the experiment which consisted of imagining the hand resting on a table, palm facing down, and propelling a small disk 10 cm with the little finger (i.e. abduction). Performance was based on failure to propel the disk 10 cm and resulted in an “error”. This allowed all subjects to begin the experiment with similar abilities in performing the task. They then immobilized the dominant upper limb of 24 subjects for a period of 7 days during which the experimental group performed motor imagery of a specific task while the control group did not. Motor imagery training used an audiotape to guide subjects through 300 repetitions of the task. After 7 days, actual performance of the motor task was assessed (total errors) and revealed no differences in performance between those who used imagery and those who did not. It is not known whether the results would have differed if visual guidance or verbal guidance were provided rather than auditory cues.

Liu and colleagues (Liu et al. 2004), assigned 46 stroke patients to either the physical or physical plus motor imagery training group to promote re-learning of functional tasks (i.e. eating, using the telephone, folding laundry, making the bed and preparing fruit). In addition to 15 one hour sessions of physical training during a three week period, subjects in the imagery group were shown a series of 15 computer-generated pictures related to the tasks and were required to imagine the task and identify the following: 1) at which point they would have difficulties executing the task if they were to physically perform it and 2) how they would overcome the difficulties of performing this task. Subjects in the imagery plus physical practice group were able to re-learn and physically perform most tasks better than the group without mental practice (higher
scores on the Fugl-Meyer Assessment) and unlike the physical practice group were able to retain these physical improvements after 1 month indicating the value of visual guided motor imagery.

**STATEMENT OF THE PROBLEM**

Studies support the use of auditory and visual guided motor imagery although none have conducted a comparison of strategies. The question of relative effectiveness is an important one if motor imagery is to be used most effectively. This study explores the effect of strategy and its influence on motor cortical excitability. More specifically, the aims of the current study were to investigate:

- The relative effectiveness of specific motor imagery strategies for increasing corticospinal excitability.
- Whether younger (20-35 years) and older (over 55 years) adults were equally able to use motor imagery to augment corticospinal output.
- Whether changes in corticospinal excitability were restricted to the muscle targeted by the motor imagery strategy.
- Whether there were hemispheric differences in the extent of corticospinal excitability modulation for the different motor imagery strategies used.

The results will provide insight into motor imagery that may be applied to physical rehabilitation where the use of motor imagery as an adjunct to therapy holds promise.
This study used a repeated measures design to determine if different motor imagery strategies influence corticospinal excitability in young and older healthy individuals.

PARTICIPANTS

Fifteen subjects between the ages of 20 and 35 years and fifteen subjects over the age of 55 years who reported themselves as healthy were recruited through word of mouth and posted advertisements. Procedures were approved by the Queen’s University and Affiliated Hospital Research Ethics Board. All subjects provided signed consent prior to beginning the study. Subjects were screened to exclude those with contraindications to TMS including intracranial metal implants, cochlear implant(s), a cardiac pacemaker, a history of epilepsy (Reid 2003) or brain injury.

OUTCOME MEASURES

All measures were obtained during a single visit to the Motor Performance Laboratory lasting 90 minutes. In all cases, motor imagery ability and working memory were assessed first, followed by TMS testing to explore the effectiveness of motor imagery strategies.

Motor Imagery Ability

Motor imagery ability was assessed using the KVIQ (Appendix 1) and a chronometric test. The KVIQ includes 10 gestures consisting of the following
movements: head flexion/extension, shoulder elevation, forward shoulder flexion to vertical, elbow flexion/extension, finger opposition, trunk flexion, knee extension/flexion, hip abduction, foot tapping and external rotation of the foot. Each movement was first demonstrated by the experimenter, after which the subject physically performed it once. Subjects were then asked to close their eyes and imagine seeing themselves perform the movement without actually moving, and to focus on the clarity of the movement in their mind’s eye. Subjects rated the clarity of the image on a scale of 1 to 5; where 1 = “no image” and 5 = “image as clear as seeing” to provide an indicator of visual imagery ability. Each movement described above was repeated, however this time, subjects were asked to imagine the sensation associated with the physical movement and to rate the intensity of the sensation, where 1 = “no sensation” and 5 = “as intense as executing the action”. This provided an indicator of kinesthetic imagery ability. The KVIQ has been validated for internal consistency for both the visual and kinesthetic components with Cronbach’s α of 0.94 and 0.92, respectively (Malouin et al., 2007).

Chronometric testing required subjects to touch two dots placed 30 cm apart with the index finger of their dominant and non-dominant hands. They were instructed to alternate between dots until told to stop (after five touches). The time taken to complete five repetitions was recorded. A second trial was completed after which subjects imagined performing the task. With eyes closed and hands on their lap they imagined physically performing the task saying “now” when they “touched” a dot. The time it took them to imagine reaching the target five times was recorded and the motor imagery ratio (imagined time/executed time) was calculated (Malouin et al. 2008b). This test was
repeated for the other hand (order determined randomly). This test has been shown to have very good to excellent reliability (ICC range from .77 to .97) (Malouin et al. 2008).

**Working Memory**

Working memory, or short term memory, refers to a limited capacity system which is responsible for the temporary storage and processing of information (Baddeley 1986). Motor imagery requires subjects to maintain both visual and kinesthetic information within their working memory. Working memory has 3 domains: visuospatial, kinesthetic and verbal (Dolman et al. 2000). Dolman and colleagues (Dolman et al. 2000) claim that motor imagery involves all 3 working memory domains, thus any impairment in working memory may impact ones motor imagery ability (Malouin et al. 2004).

All domains of working memory were evaluated using a standardized procedure involving the measurement of immediate serial recall (Appendix 2). Each domain was tested using an initial sequence (or span length) of two items. If subjects accurately reproduced three out of five unique trials at that span length, then the number of items was increased by one and testing repeated. This process continued until subjects either failed to reproduce at least 3/5 trials at a given span length or when the maximum span length was achieved.

To assess the verbal domain, a list of one syllable words was provided verbally to subjects and they repeated the list in the same order. The maximum span length possible was 9.

The visuospatial domain was evaluated by having subjects seated in front of nine blocks (3 cm cubes). The blocks were numbered 1-9, with the numbers facing the evaluator only who would tap the blocks in a random sequence. Subjects sat across from
the evaluator and were asked to repeat this sequence. The maximal span length possible was 9.

The kinesthetic domain was evaluated by having subjects reproduce a sequence of gestures. Subjects were seated on a chair with their eyes closed and hands placed on their thighs. The evaluator, seated facing the subject, passively moved the subject’s dominant upper limb through a sequence of movements (for example abduction of the arm followed by tapping the opposite shoulder). Subjects were asked to reproduce the same sequence of gestures with their non-dominant limb while keeping their eyes closed. The maximal span length was six (Malouin et al. 2004).

For each domain the total number of correct responses in each set of five trials and the last successful span length were recorded.

Corticospinal excitability

Corticospinal excitability was assessed using TMS. TMS was delivered via a figure-of-eight coil (external wing diameter of 70mm). Small adhesive surface electrodes (Ag-AgCl) were placed bilaterally in a bipolar configuration on the muscle bellies of 3 hand muscles: FDI, ADM and APB. A common reference was placed on the wrist slightly lateral to the ulnar styloid process. Although FDI was the target muscle, muscle activity in both ADM and APB muscles were monitored to assess whether motor imagery strategies facilitated only the target muscle. EMG signals were bandpass filtered (30 Hz – 1kHz), amplified 1000 times (Bortec Biomedical Ltd, Calgary, Alberta), and digitized at 2KHz using (National Instruments A/D model, Austin, TX). A 50ms baseline preceded the delivery of TMS and a 300ms post-stimulus EMG record was obtained.
Subjects sat in a chair with their arms resting on a table (Figure 1). Each subject wore a Lycra bathing cap upon which the intersection of a line formed between the tragi and a line extending from the nasion to inion was marked. TMS intensity was initially set to 60% of the stimulus output and applied about three cm lateral to the vertex. The optimal stimulus site (which evoked the largest MEP in the contralateral FDI) was identified and marked.

Figure 1. Experimental set up. Subjects were seated in front of a computer screen while TMS was applied overlying the motor cortex.

Resting motor threshold (MT), the lowest intensity needed to elicit an MEP of at least 50µV in amplitude in response to 5 out of 10 stimuli in the relaxed FDI muscle was determined (Pascual-Leone, Grafman & Hallett 1994). The intensity was then set to 120%
MT for the remainder of the protocol. The peak to peak amplitude of the MEP was measured and the average of each five responses calculated for each condition.

Motor Imagery Procedures

Subjects began by physically practicing index finger abduction by pushing a block against a sponge (Figure 2). They were instructed to focus on the sensations associated with the task and were given time to imagine the task while focusing on the clarity and sensations associated with this movement. When the subject indicated they were able to focus solely on index finger abduction, were comfortable imaging the movement and no visible EMG from any of the muscles of interest were evident, then testing began. A block of 5 stimuli were first introduced while subjects closed their eyes and cleared their minds of any thoughts. Following these baseline recordings visual, auditory and combined visual and auditory strategies were introduced in randomized sequence interspersed with rest and muscle activation conditions. Prior to performing an imagery strategy, subjects would physically perform index finger abduction once, following the suggested ratio of 1:5 (physical to imagery) which is considered optimal for ensuring a strong memory trace (Malouin et al. 2004).
Figure 2. Subjects were instructed to perform index finger abductions by pushing a block against a sponge on a wooden block.

**Visual Strategy** Subjects were seated in front of a computer screen, displaying a video of a person performing index finger abduction. The video was specific to both gender and side such that a male subject would view a man’s hand showing either right or left index finger abduction depending on whether the subject was imagining performance with the right or left finger. Subjects were instructed to imagine the image as their own hand. TMS was delivered to the contralateral hemisphere at random times during the video image of the finger pushing the block against the sponge.

**Auditory Strategy** Subjects closed their eyes and imagined performing left or right finger abductions while being guided by a verbal cue instructing them to “push the block” and then to “release” it. TMS was applied between 2-5 seconds after the verbal cue to push the block had been given and before the release command was given.
**Combined Strategy** Subjects watched the video of index finger abduction which was supplemented by verbal cues. As with the visual and auditory strategies, TMS was delivered at random intervals after the cue was initiated.

**Rest Condition** TMS was delivered while subjects closed their eyes and cleared their minds of any thoughts.

**Activation Condition** Subjects were asked to physically perform the isolated index finger abduction task. Once they gently pushed the block against the sponge, TMS was delivered.

**DATA ANALYSIS**

Each component of the KVIQ (visual and kinesthetic) yielded scores for the dominant and non-dominant limb and a total score (i.e. neck flexion/extension, shoulder elevation trunk flexion). For each component the individual scores for the dominant (maximum score of 35) and non-dominant (maximum score of 35) sides were summed. Both these scores were averaged and added to the remaining three scores from tasks that were not lateralized to produce the total score (maximum score of 50). Independent t-tests were used to determine whether there were differences in scores between young and older individuals.

A two-way repeated measures analysis of variance (ANOVA) was performed to determine whether chronometric scores differed between groups and as a function of hand dominance.
For working memory, span length and the total number of correct responses were compared across groups using independent t-tests to determine if young and older subjects performed differently with “arm” (dominant, non-dominant) as the within subject factor and “group” (younger, older) as the between subject factor.

To evaluate corticospinal excitability, the peak to peak amplitude of the average MEP was determined for each motor imagery strategy and expressed as a percentage of the MEP amplitude associated with the baseline rest condition. This normalization permits between group and between condition comparisons.

To address the question of whether MEPs were enhanced as a result of a specific motor imagery strategy and whether changes in corticospinal excitability are restricted to the muscle targeted by a given motor imagery strategy, a repeated measures ANOVA was performed. Within subject factors were “strategy” (rest, visual, auditory, activation and combined), “hemisphere” (dominant, non-dominant) and “muscle” (APB, FDI, ADM). The between subject factor was group (younger, older).

Post hoc analyses (Bonferroni) were carried out where appropriate to determine where the differences lay. The level of significance was in all cases p<0.05.
Chapter 4: Results

Fifteen young (mean ± 1SD age: 26.6±2.38 years) and fifteen older (mean ± 1SD age: 67.2±7.03 years) healthy adults participated and completed all aspects of the study. The younger group consisted of eight females and seven males whereas the older group had 10 females and five males. Handedness was determined by asking subjects which hand they wrote and ate with. Both groups had 14 right handed individuals and one who was left handed.

MOTOR IMAGERY ABILITY

Scores for the KVIQ and chronometric test are summarized in Table 1. Independent t-tests were performed to determine whether there were any differences in motor imagery ability between young and older adults. Results revealed that both groups had similar scores on the visual component of the KVIQ for the dominant hand (p=0.650) and non-dominant hand (p=0.667). Scores for the kinesthetic component of the KVIQ were also similar between groups for both dominant hand (p=0.845) and non-dominant hand (p=0.940). It follows that the total KVIQ score was comparable between groups (p=0.491).
Chronometric testing assessed the temporal congruence between the time taken to imagine and execute a task. In all cases the ratio was greater than 1.0 indicating that subjects took longer when imagining themselves performing the task than when they physically executed it. Repeated measures ANOVA showed that both groups took longer to imagine the task with their dominant arm compared to their non-dominant arm (p=0.026). No interactions were seen between group and arm (F=0.958, p=0.336). Chronometric scores are illustrated in figure 3.

Figure 3. Chronometric scores (mean±1SD) for younger and older subjects. * = p<0.05
WORKING MEMORY

In order to perform motor imagery, the representation of a motor task must be reproduced within working memory. Accordingly, working memory was assessed to ensure that subjects did not exhibit any impairment, which could negatively affect their ability to engage in motor imagery. Working memory scores for each of the domains are presented in Table1. No age related differences were found in the verbal domain for either span length (p=0.506) or total correct responses (p=0.414), meaning that both groups were able to recall a list with a similar number of words. In contrast, the younger group recalled more items in both kinesthetic (p=0.001) and visuospatial domains (p=0.018).
Table 1. Summary of KVIQ and working memory scores (mean±SD).

<table>
<thead>
<tr>
<th>KVIQ Scores</th>
<th>Young Group N = 15</th>
<th>Older group N = 15</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Visual</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dominant Side (max=35)</td>
<td>28.1±5.8</td>
<td>28.1±5.6</td>
<td>1.000</td>
</tr>
<tr>
<td>Non-dominant side (max=35)</td>
<td>28.3±5.7</td>
<td>27.7±5.7</td>
<td>0.750</td>
</tr>
<tr>
<td>Total (max=50)</td>
<td>40.9±7.5</td>
<td>39.7±7.3</td>
<td>0.650</td>
</tr>
<tr>
<td><strong>Kinesthetic</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dominant Side (max=35)</td>
<td>24.1±7.4</td>
<td>23.6±7.4</td>
<td>0.845</td>
</tr>
<tr>
<td>Non-dominant side (max=35)</td>
<td>22.7±7.5</td>
<td>22.9±6.8</td>
<td>0.940</td>
</tr>
<tr>
<td>Total (max=50)</td>
<td>33.6±9.6</td>
<td>33.2±9.9</td>
<td>0.919</td>
</tr>
<tr>
<td><strong>Total KVIQ</strong></td>
<td>74.5±16.0</td>
<td>72.9±12.7</td>
<td>0.764</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Working Memory Domains</th>
<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td><strong>Verbal Domain</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(max span length = 8)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Span Length</td>
<td>6.6±1.2</td>
<td>6.3±1.0</td>
<td>0.506</td>
</tr>
<tr>
<td>Total Correct Responses</td>
<td>21.8±5.6</td>
<td>20.3±4.0</td>
<td>0.414</td>
</tr>
<tr>
<td><strong>Visuospatial Domain</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(max span length = 8)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Span Length</td>
<td>6.3±0.7</td>
<td>5.6±0.8</td>
<td>0.015</td>
</tr>
<tr>
<td>Total Correct Responses</td>
<td>20.7±3.5</td>
<td>17.5±3.6</td>
<td>0.018</td>
</tr>
<tr>
<td><strong>Kinesthctic Domain</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(max span length = 6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Span Length</td>
<td>5.1±0.9</td>
<td>3.7±0.8</td>
<td>0.001</td>
</tr>
<tr>
<td>Total Correct Responses</td>
<td>14.8±4.7</td>
<td>8.4±3.6</td>
<td>0.001</td>
</tr>
</tbody>
</table>
CORTICOSPINAL EXCITABILITY AND MOTOR IMAGERY STRATEGIES

Data were not normally distributed, therefore a Greenhouse-Geisser correction was used for all dependent measures. Motor threshold were similar in both dominant (p=0.258) and non-dominant hemispheres (p= 0.458). Prior to performing the motor imagery trials, baseline MEPs were recorded from all subjects as they sat in a chair with their eyes closed and relaxed. A 2-way repeated measures ANOVA revealed that MEPs were of similar amplitude for both groups and that MEPs from the FDI muscle were larger in amplitude than APB (p=0.014) and ADM (p=0.005) muscles. No differences were detected between responses elicited following stimulation of dominant and non-dominant hemispheres. No interactions between group and hemispheres were found (p=0.951). Motor thresholds and MEP amplitudes are summarized in Table 2.

Table 2. Mean motor threshold and baseline MEPs (±SD) by group, hemisphere and muscle.

<table>
<thead>
<tr>
<th></th>
<th>Younger Group</th>
<th>Older Group</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dominant Hemisphere</td>
<td>Non-Dominant Hemisphere</td>
<td></td>
</tr>
<tr>
<td>Motor Threshold (%)</td>
<td>47±7</td>
<td>52±10</td>
<td>50±6</td>
</tr>
<tr>
<td>Baseline MEP (mV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APB</td>
<td>0.03±0.03</td>
<td>0.07±0.08</td>
<td>0.14±0.25</td>
</tr>
<tr>
<td>*FDI</td>
<td>0.19±0.10</td>
<td>0.17±0.19</td>
<td>0.21±0.21</td>
</tr>
<tr>
<td>ADM</td>
<td>0.06±0.12</td>
<td>0.05±0.04</td>
<td>0.21±0.37</td>
</tr>
</tbody>
</table>

*p <0.05 significant effect of muscle as determined by repeated measures ANOVA
APB= abductor pollicis brevis; FDI= first dorsal interosseous; ADM=abductor digiti minimi; MEP=motor evoked potential.
A repeated measures ANOVA demonstrated that MEP amplitudes associated with the rest condition were significantly smaller than those elicited during any of the 3 imagery strategies or the activation condition (p=0.001). During FDI activation, MEPs were largest in all muscles (p=0.001). Imagery- induced facilitation of MEPs however, was similar for all 3 imagery strategies (p>0.05). An interaction of hemisphere, group and strategy (F= 4.022; p= 0.048) was detected reflecting that the MEPs were larger when the older group’s dominant hemisphere was stimulated while performing imagery under auditory guidance. A representative example of the MEPs recorded from a subject in the younger group is presented in Figure 4.
Figure 4. MEPs elicited from the FDI muscle following stimulation of the dominant and non-dominant hemispheres during motor imagery and at rest for one subject. The arrow indicates delivery of TMS pulse.
DO MOTOR IMAGERY STRATEGIES TARGET A SPECIFIC MUSCLE?

At rest, no differences were found between mean MEP amplitudes elicited from any of the 3 muscles (F=2.418, p=0.120). When subjects used the visual imagery strategy, MEPs in the FDI muscle were larger than in APB (p=0.006) and ADM (p=0.001) muscles whereas the MEPs from APB and ADM muscles were comparable in amplitude. With the auditory and the combined strategies as well as during FDI activation, both FDI and ADM muscles generated comparable MEPs (p>0.05). However, mean MEP amplitude of the FDI muscle was significantly larger than the APB muscle (p<0.05). Table 3 summarizes these findings.
Table 3. Mean ±1SD MEP amplitudes (normalized to baseline) by group, muscle and hemisphere. Stimulation intensity was 120% of motor threshold.

<table>
<thead>
<tr>
<th></th>
<th>Younger Group</th>
<th>Older Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>APB</td>
<td>FDI</td>
</tr>
<tr>
<td><strong>Rest</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dom</td>
<td>0.17±0.66</td>
<td>0.13±0.83</td>
</tr>
<tr>
<td>Non-Dom</td>
<td>0.24±1.53</td>
<td>-0.05±0.68</td>
</tr>
<tr>
<td><strong>Visual</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dom</td>
<td>1.30±2.29</td>
<td>2.27±2.28</td>
</tr>
<tr>
<td>Non-Dom</td>
<td>1.06±1.83</td>
<td>1.48±1.03</td>
</tr>
<tr>
<td><strong>Auditory</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dom</td>
<td>0.72±1.06</td>
<td>1.94±2.38</td>
</tr>
<tr>
<td>Non-Dom</td>
<td>0.61±1.39</td>
<td>1.18±1.63</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dom</td>
<td>1.07±1.09</td>
<td>2.78±4.40</td>
</tr>
<tr>
<td>Non-Dom</td>
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<td>1.15±1.00</td>
</tr>
<tr>
<td><strong>Activation</strong></td>
<td></td>
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</tr>
<tr>
<td>Dom</td>
<td>3.99±4.23</td>
<td>13.45±13.80</td>
</tr>
<tr>
<td>Non-Dom</td>
<td>1.10±1.58</td>
<td>8.38±8.40</td>
</tr>
</tbody>
</table>

Dom=dominant hemisphere; Non-Dom=non-dominant hemisphere; APB= abductor pollicis brevis; FDI= first dorsal interosseous; ADM=abductor digiti minimi; MEP=motor evoked potential
MEP amplitude of the FDI muscle differed as a function of hemisphere during the auditory strategy (p=0.037) such that they were larger when TMS was applied to the dominant hemisphere. Hemispheric differences were also found in association with the visual strategy (p=0.043) but not for the combined strategy (p=0.160).

During FDI activation, the groups differed as a function of hemisphere stimulated (F=5.004, p=0.033) such that activation-induced MEPs were larger in the dominant FDI for the younger group, and larger in the non-dominant FDI for the older group. Mean MEP amplitudes for FDI, ADM and APB during motor imagery are illustrated in Figure 5.
Figure 5. Mean (±1SD) MEP amplitudes (normalized to baseline values) for APB, FDI, and ADM muscles elicited during motor imagery of index finger abduction using visual, auditory and combined strategies. Note: Since there were no differences between the young group and older group, data were pooled. $* = p < 0.05$
Chapter 5: Discussion

The main findings of this study were that motor imagery strategies increase motor
cortical output, although not differentially. Older subjects yielded lower visuospatial and
kinesthetic working memory domain scores than their younger counterparts, but this did
not influence the effectiveness of motor imagery. When imagining an index finger
abduction task with visual, auditory or combined cueing, MEPs increased significantly in
amplitude over the rest condition, but only visual imagery limited facilitation to the FDI
muscle whereas, for all other strategies the MEPs in both FDI and ADM muscles were
enhanced. Auditory and visual imagery strategies elicited larger MEPs in the FDI muscle
when subjects imagined physical movement of the index finger of the dominant hand.

WORKING MEMORY, IMAGERY ABILITY AND AGE - HOW DO THEY
RELATE TO MOTOR IMAGERY?

In the present study, both groups obtained similar scores for the verbal domain of
working memory whereas the younger group performed better than the older group in
both kinesthetic and visuospatial domains. A decline in working memory related to age
has been suggested by several studies (Babcock, Salthouse 1990, Salthouse et al. 1989,
specifically, age related declines in visuospatial (Bopp, Verhaeghen 2007, Dolman et al.
2000, Hester, Kinsella & Ong 2004, Jenkins et al. 2000) and kinesthetic working memory
(Dolman et al. 2000) have been reported and are supported by the current findings.

The current study did not show any influence of age on motor imagery ability,
which was measured via KVIQ and chronometric testing. These results are in accordance
with Léonard et al. (Leonard, Tremblay 2007) who also concluded that one’s ability to imagine is preserved with age. In contrast, other studies have demonstrated that there are age related decrements in one’s ability to perform mental imagery tasks (Craik, Dirkx 1992, Dror, Kosslyn 1994). More precisely, the ability to manipulate an image within the mind (Craik, Dirkx 1992), the speed and accuracy at which they can imagine a task (Craik, Dirkx 1992, Dror, Kosslyn 1994) have all been shown to decrease as a function of age.

Motor performance improvements seen after motor imagery training appear to be related to the level of working memory (Malouin et al. 2004). Malouin and colleagues (Malouin et al. 2004) reported that after a single session of imagery training, subjects with high visuospatial working memory scores demonstrated better long term retention of the learned motor task than those with poor working memory scores. The findings suggest that an adequate level of working memory is necessary to retain the motor learning benefits of motor imagery.

EFFECTIVENESS OF MOTOR IMAGERY STRATEGIES

Using TMS, a series of studies have provided evidence that motor imagery increases corticospinal excitability relative to rest (Abbruzzese et al. 1999, Clark, Tremblay & Ste-Marie 2004, Leonard, Tremblay 2007, Li 2007, Marconi et al. 2007, Rossini et al. 1999, Yahagi, Kasai 1998, Yahagi, Kasai 1999). In accordance with these findings, the present study also revealed that motor imagery is associated with larger MEPs when compared to a rest condition. Subjects were asked to imagine a task requiring index finger abduction while being guided by either visual, auditory or
combined cueing as a strategy to improve the effectiveness of imagery. Results failed to show any differences in the relative effectiveness of these imagery strategies, although all showed an approximate 23-fold increase in motor cortical output over rest. In a similar study, Clark et al. (Clark, Tremblay & Ste-Marie 2004) examined corticospinal excitability during movement observation and motor imagery of various hand actions. MEPs elicited by TMS were measured under five conditions: passive observation; observation with intent to imitate; motor imagery (imagining an OK sign of the thumb); imitation (physical activation); and counting. Facilitatory effects were revealed only in conditions wherein participants were either mentally (passive observation, observation with intent to imitate and motor imagery) or physically engaged in performing actions. No differences in MEP amplitudes were found between observation and motor imagery.

In the present study, visual cueing was used to help guide subjects during imagery. This strategy helped subjects limit facilitation to the target muscle during index finger abduction. Prior to addressing the specificity of facilitation, the benefit of task observation, must first be considered, which according to Hayes et al. (Hayes et al. 2006) is the most effective method to acquire a new skill. Motor learning by means of motor imagery has been validated in previous studies (Mulder et al. 2004, Pascual-Leone et al. 1995, Ranganathan et al. 2004, Yaguez et al. 1998). Visual stimuli depicting human action activates similar cortical regions as those active during motor imagery, movement planning and motor learning. These areas include the basal ganglia, prefrontal cortex, parietal cortex and SMA (Cross, Hamilton & Grafton 2006, Halsband, Lange 2006). Hayes et al. (Hayes et al. 2006) explored whether skill acquisition was acquired more effectively through physical practice or through observational learning. Subjects were
divided to 1 of 4 groups: physical practice and demonstration (where subjects viewed a man perform the perfect movement to accomplish the task effectively and practiced the task), physical practice only (no demonstration), demonstration only (no physical practice), and control (no physical practice or demonstration). Participants were required to learn a novel bowling action. Results revealed that the physical practice and demonstration group were able to emulate the bowling task more accurately compared to the other groups resulting in better performance of the novel task. These findings were extended by Al-Abood et al. (Al-Abood, Davids & Bennett 2001) who compared the efficacy of visual demonstration and verbal instructions at promoting skill acquisition. Participants without any dart throwing experience were required to learn a dart throwing task with their dominant hand. Subjects were randomly assigned to one of the three groups including a control group (no guidance or instruction), a verbally directed group (verbal instructions were provided as to how to accurately perform the task), or an observation group (shown a video demonstrating how to properly perform the task). Subjects in the observation group were able to learn the task more quickly and accurately compared to the other groups. Clearly, task observation seems to promote motor learning. The current study extended these findings by demonstrating the effectiveness of observation at isolating the benefits of motor imagery to the target muscle only.

MEPs were recorded from APB, FDI and ADM muscles of the hand while subjects imagined abducting either their left or right index finger only with the assistance of visual, auditory and combined cueing. Regardless of age group or side involved in the imagined task, only the visual strategy was associated with targeted MEP facilitation in
the FDI muscle. With auditory and combined strategies, both FDI and ADM muscles were facilitated by imagery, but not APB. Studies exploring the specificity of motor imagery have produced conflicting results. Motor imagery with auditory cueing has been found to be ineffective at restricting facilitation to the prime mover (Marconi et al. 2007) as agonist and antagonist muscle responses were augmented with imagery. Others have reported selective facilitation during imagery with auditory guidance, such that the FDI muscle alone was responsive to TMS during index finger abduction (Rossini et al. 1999) and restricted facilitation has been seen in the APB muscle during imagery of thumb abduction (Facchini et al. 2002). Other studies have reported isolated facilitation of the target muscle while observing an action (Fadiga et al. 1995, Maeda, Kleiner-Fisman & Pascual-Leone 2002, Patuzzo, Fiaschi & Manganotti 2003, Strafella, Paus 2000). Action observation is a cognitive function that combines higher order visual areas with motor planning to directly match the observed action with the observer’s own prototype of this action (Rizzolatti, Fogassi & Gallese 2001). Cortical regions, including those involved in motor planning (Facchini et al. 2002), are activated during both motor imagery and movement observation (Binkofski et al. 1999, Kosslyn, Behrmann & Jeannerod 1995, Rizzolatti et al. 1996) and regions involved in voluntary movement have been activated during action observation (Grafton et al. 1996). In a study by Maeda and colleagues (Maeda, Kleiner-Fisman & Pascual-Leone 2002) subjects observed a thumb abduction movement while EMG recordings were taken from APB and FDI muscles in response to TMS. The hand in the video being watched by the subject was presented either in the same orientation as that of the subject’s own hand (1st person) or as though watching someone facing them (3rd person). Results revealed isolated MEPs from the
APB muscle only when the hand orientation was compatible with the subject’s own hand indicating that first person perspective is important.

Findings by Marconi et al. (Marconi et al. 2007) however, showed that both the target muscle (APB) and a functionally related muscle (FDI) were activated when observing thumb opposition, though other muscles (ADM, extensor digitorum communis and flexor digitorum superficialis muscles) in the vicinity remained silent. Marconi’s subjects watched the experimenter’s hand through a panel, i.e. mirroring the subjects own hand which Maeda et al. reported less effective in isolating the effect (Maeda, Kleiner-Fisman & Pascual-Leone 2002). The visual cueing used in the present study was from a 1st person perspective that unlike other strategies, targeted only the muscle involved in the imagined task.

During physical activation, excitability of the specific muscle representation in the M1 is selectively modulated in accordance with the muscle(s) involved in the task (Garry, Kamen & Nordstrom 2004, Stinear, Byblow 2004). This is achieved by decreasing the activity of intracortical inhibitory interneurons prior to and during a motor task (Garry, Kamen & Nordstrom 2004, Stinear, Byblow 2003b). The relative balance between excitatory and inhibitory input to corticospinal neurons will determine the amplitude of the MEP and this is believed to be fundamental to motor learning (Garry, Kamen & Nordstrom 2004, Reynolds, Ashby 1999). It has been revealed that stimulation of a single pyramidal neuron produces responses from multiple muscles (Cheney, Fetz 1985). Accordingly, when attempting to physically move one finger, activation can be seen in motoneurons of all fingers (Hager-Ross, Schieber 2000); a phenomenon known as enslaving (Zatsiorsky, Li & Latash 1998). During motor imagery (Abbruzzese et al.
1999, Stinear, Byblow 2004) and movement observation (Patuzzo, Fiaschi & Manganotti 2003, Strafella, Paus 2000) increases in ICI to muscles in proximity to the prime movers occur, however, whether these increases are associated with restricting facilitation to the target muscle is not clear. Stinear et al. (Stinear, Byblow 2004) recorded EMG from APB and ADM muscles while subjects imagined pushing their thumb onto a table. Relative to rest, imagery-induced MEPs were significantly larger in the APB muscle compared to the ADM muscle, and the level of ICI was greater in the ADM muscle, which likely contributed to focusing the response to the muscle targeted by motor imagery. No study, however, has compared the relative effectiveness of motor imagery strategies on ICI in muscles not targeted by motor imagery (but in close proximity) as well as the prime mover. While the current study did not measure ICI, it is possible that isolated facilitation of the target muscle during visually cued motor imagery may have increased the level of ICI to ADM and APB. Visual cueing may therefore more closely approximate physical execution which also restricts movement to target muscles.

ARE THERE HEMISPHERIC DIFFERENCES IN THE EFFECTIVENESS OF MOTOR IMAGERY STRATEGIES?

Visual cueing

It is well established that a specific neural system is activated when an action is being observed (Buccino, Binkofski & Riggio 2004, Fecteau, Lassonde & Theoret 2005, Iacoboni, Mazziotta 2007, Kilner, Friston & Frith 2007, Miall 2003, Molnar-Szakacs et al. 2005, Rizzolatti, Craighero 2004). This system, known as the mirror neuron system (MNS), was originally described in the premotor cortex of a monkey (Gallese et al. 1996,
It was later shown to exist in the human brain (Iacoboni et al. 1999, Rizzolatti, Fogassi & Gallese 2001) and is believed to be critical in helping people learn motor tasks through observation (Buccino, Binkofski & Riggio 2004). It has been suggested that the MNS lies within the left hemisphere (Fecteau, Lassonde & Theoret 2005) which may explain why subjects in the current study elicited larger MEPs from the domainant FDI muscle when being guided by a visual cue. Fecteau and colleagues (Fecteau, Lassonde & Theoret 2005) studied a split brain patient who had a complete corpus callosotomy hypothesizing that if the MNS is active primarily in the left hemisphere then facilitation through observation should be greatest when observing movements of the right hand. While the patient viewed movie clips from a computer screen, TMS induced MEPs were elicited from left or right APB muscles. Three conditions were observed including: translation of the right finger, translation of the left finger, or rest (baseline). MEP facilitation from the left hemisphere was significantly greater, suggesting a dominant effect of the left hemisphere in the activation of MNS. Healthy control subjects demonstrated comparable results as the split brain patient.

**Auditory cueing**

It has been hypothesized that there may be phylogenetic connections between the motor cortex and language areas of the brain (Meister et al. 2003, Rizzolatti, Arbib 1998, Tokimura et al. 1996). The present study showed greater motor output from the left hemisphere during motor imagery of finger abduction while being guiding by auditory cuing. The functional connection between cortical areas involved in language and the hand area of the motor cortex appears to be predominantly in the left hemisphere.
(Hauk, Johnsrude & Pulvermuller 2004, Meister et al. 2003, Papathanasiou et al. 2004, Tokimura et al. 1996) explored how action words affiliated with a body part (i.e. lick (tongue), pick (arm), kick (legs)) would differentially activate motor cortical areas. fMRI data from Hauk and colleagues showed that words are processed in neural circuits reflecting their semantics linked to cortical areas largely in the left hemisphere. This may explain the findings of the current study showing increases in corticospinal excitability during motor imagery of the right hand in particular with guidance by verbal cueing.

Although studies have shown that cortical motor areas are activated during language perception, the underlying mechanisms remain unclear. One hypothesis is that the MNS is not only involved in action observation but in action understanding as well (Binkofski, Buccino 2006). This has been supported by a recently identified link between the MNS and language (Arbib 2005). Similarities in function between the monkey’s premotor area F5 and Broca’s area in humans supports the relationship between MNS and language (Arbib 2005). Given that Broca’s area is situated in the left hemisphere (Kandel, Schwartz & Jessell 2000), it is possible that this is why most studies, including the current study, have shown left hemisphere dominance of language based cueing (Hauk, Johnsrude & Pulvermuller 2004, Meister et al. 2003, Papathanasiou et al. 2004, Tokimura et al. 1996).

**Combined imagery strategy**

Unlike the auditory and visual strategies, the combined strategy did not isolate facilitation to the target muscle or result in larger responses elicited from the dominant hemisphere. This finding contradicts Aziz-Zadeh et al. (Aziz-Zadeh et al. 2004) who put
forward the idea that a greater number of modalities used (i.e. auditory and visual) to promote motor facilitation in the left hemisphere would result in larger motor responses. This assumption was based on their results which demonstrated that the MNS has different methods of coding for an action depending on which hemisphere is being used. In the left hemisphere actions were coded through auditory, visual and motor components, whereas in the right hemisphere action coding occurred via visual and motor channels. It can be postulated that although visual and auditory cueing are individually effective during imagery, concurrently they may cause interference. Divided attention during motor imagery can greatly impact its effectiveness (Sharma, Pomeroy & Baron 2006). Cross-modal attention paradigms demonstrated that overloading the sensory system and forcing divided attention between two modalities such as vision and listening causes a net reduction in attention (Alais, Morrone & Burr 2006, Rees, Frith & Lavie 2001). In the current study it is likely that subjects focused on one or the other cue which may explain why there was no added benefit of combining both cues. In addition, it is also possible that there was a temporal lag between the auditory and visual cue in the combined strategy, adversely affecting the clarity of the image causing a lack of synchronization. Showing a video of a finger task with the hand orientation opposite to that of the subject’s hand produces similar discordance which when present has been shown to be less effective at promoting imagery (Maeda, Kleiner-Fisman & Pascual-Leone 2002). The extent to which a lack of synchronization between cueing strategies during motor imagery creates interference reducing the effectiveness of imagery warrants further investigation.
One of the challenges in studying motor imagery is that it is not known what the individual is mentally rehearsing and experiencing. One method used to guide someone as they imagine is using a strategy such as auditory or visual guidance. These strategies provide cues to focus subject’s attention indicating when to begin and stop imaging the motor task, what pace to maintain and descriptors of what to imagine. This study revealed that in young and older subjects visual cueing augments motor cortical output to the muscle targeted by motor imagery and visual and auditory cueing both facilitate MEPs, but to a greater extent when the left hemisphere is involved.
Chapter 6: Conclusion and Future Directions

This study examined whether motor imagery strategies differentially modulated corticospinal excitability as young and older subjects imagined themselves performing an index finger abduction task. The relative effectiveness of a given strategy at targeting facilitation to the FDI muscle was also determined. Finally, it was investigated whether motor imagery was equally effective when the imagined task involved the right or left FDI. The major findings of this study are as follows:

- All motor imagery strategies increased motor cortical output relative to a resting condition
- Only the visual strategy limited facilitation to the muscle primarily involved (FDI) in the imagined task.
- TMS induced MEPs were greater in amplitude when the left hemisphere was stimulated during motor imagery while being guided by either auditory or visual cueing.

This study was the first to evaluate the relative effectiveness of motor imagery strategies on corticospinal excitability in young and older adults. The results indicate that while imagery enhances motor cortical output, a visual imagery strategy is best at isolating facilitation to the prime mover of the imagined task. Visual and auditory strategies are more effective when right index finger abduction imagined compared to
left index finger. Combining these 2 strategies did not show any added benefit. There were no differences in imagery effectiveness between young and older groups.

The current study explored various imagery strategies in healthy adults, however, it is not known if the findings would be replicated in stroke patients. Furthermore, the results of this study indicate that imagery of the right hand was generally more effective at facilitating cortical output. Whether this would be affected by a lesion due to a stroke warrants further investigation.

Motor imagery is a technique which can increase motor cortical output to a significant degree. There is no cost associated with it and unlike physical practice, does not impose any risk of injury. As such, it may be an effective adjunct to treatment in rehabilitation. Further research is required to build on this study and determine if the findings can be generalized to include such clinical populations as stroke.
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APPENDIX 1
Kinesthetic and Visual Motor Imagery Questionnaire (KVIQ)

**Question 1**

1. Sitting straight, head straight and hands resting on your thighs
2. Tilt your head as far as possible, bringing it forward then backward.
3. Return to the start position. Now imagine the movement, concentrate on the clarity of the image.
4. Indicate on the scale the quality of the imagined movement

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**Question 2**

1. Sitting straight, head straight and hands resting on your thighs
2. With your arms by your side, raise both shoulders as high as possible without moving your head.
3. Return to the start position. Now imagine the movement, concentrate on the clarity of the image.
4. Indicate on the scale the quality of the imagined movement

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**Question 3**

1. Sitting straight, head straight and hands resting on your thighs
2. Lift your non-dominant arm up high, keeping it straight out in front of you and lift until it’s straight up high.
3. Return to the start position. Now imagine the movement, concentrate on the clarity of the image.
4. Indicate on the scale the quality of the imagined movement

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**Question 4**

1. Sitting straight, head straight and with your dominant arm straight out in front of you with your hand open and palm up
2. Bend your elbow of your dominant hand side as though you were going to touch your shoulder on the same side
3. Return to the start position. Now imagine the movement, concentrate on the clarity of the image.
4. Indicate on the scale the quality of the imagined movement

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**Question 5**

1. Sitting straight, head straight and hands resting on your thighs with your palms up
2. With your dominant hand, touch the tip of each finger with your thumb, start with the index finger and move along in order at the rate of about one movement/second
3. Return to the start position. Now imagine the movement, concentrate on the clarity of the image.
4. Indicate on the scale the quality of the imagined movement

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(repeat questions 3,4,5 for the other side)

**Question 6**

1. Sitting straight, head straight and hands resting on your thighs
2. Bend at the waist, moving your trunk forward as far as possible then straighten up again
3. Return to the start position. Now imagine the movement, concentrate on the clarity of the image.
4. Indicate on the scale the quality of the imagined movement

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Question 7

1. Sitting straight, head straight and hands resting on your thighs
2. Extend you knee to raise your lower leg of your non-dominant side as close as possible to horizontal then lower it
3. Return to the start position. Now imagine the movement, concentrate on the clarity of the image.
4. Indicate on the scale the quality of the imagined movement

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Question 8

1. Sitting straight, head straight and hands resting on your thighs
2. Move your foot on your dominant side out to the side about 30 cm (12 inches) then bring it back
3. Return to the start position. Now imagine the movement, concentrate on the clarity of the image.
4. Indicate on the scale the quality of the imagined movement

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Question 9

1. Sitting straight, head straight and hands resting on your thighs
2. With your non dominant leg tap your foot on the floor three times; about once/second while keeping your heel on the floor
3. Return to the start position. Now imagine the movement, concentrate on the clarity of the image.
4. Indicate on the scale the quality of the imagined movement

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**Question 10**

1. Sitting straight, head straight and hands resting on your thighs
2. Without moving your heel, turn your toes on your dominant side out to the side as far as possible
3. Return to the start position. Now imagine the movement, concentrate on the clarity of the image.
4. Indicate on the scale the quality of the imagined movement

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(repeat questions 7,8,9,10 for the other side)

**Question 11**

1. Sitting straight, head straight and hands resting on your thighs
2. Tilt your head as far as possible, bringing it forward then backward.
3. Return to the start position. Now imagine the movement, concentrate on the intensity of the sensations.
4. Indicate on the scale the quality of the imagined movement

```
5  4  3  2  1
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**Question 12**

1. Sitting straight, head straight and hands resting on your thighs
2. With your arms by your side, raise both shoulders as high as possible without moving your head
3. Return to the start position. Now imagine the movement, concentrate on the intensity of the sensations.
4. Indicate on the scale the quality of the imagined movement

```
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**Question 13**

1. Sitting straight, head straight and hands resting on your thighs
2. Lift your non-dominant arm up high, keeping it straight out in front of you and lift until it’s straight up high
3. Return to the start position. Now imagine the movement, concentrate on the intensity of the sensations.
4. Indicate on the scale the quality of the imagined movement

\[
\begin{array}{cccccc}
5 & 4 & 3 & 2 & 1 \\
\text{as intense} & \text{intense} & \text{moderately} & \text{Mildly} & \text{No} \\
\text{as executing} & \text{intense} & \text{intense} & \text{sensation} \\
\text{the action} & & & & \\
\end{array}
\]

**Question 14**

1. Sitting straight, head straight and your dominant arm straight out in front of you with your hand open and palm up
2. Bend your elbow of your dominant hand side as though you were going to touch your shoulder on the same side
3. Return to the start position. Now imagine the movement, concentrate on the intensity of the sensations.
4. Indicate on the scale the quality of the imagined movement

\[
\begin{array}{cccccc}
5 & 4 & 3 & 2 & 1 \\
\text{as intense} & \text{intense} & \text{moderately} & \text{Mildly} & \text{No} \\
\text{executing} & \text{intense} & \text{intense} & \text{sensation} \\
\text{the action} & & & & \\
\end{array}
\]
Question 15

1. Sitting straight, head straight and hands resting on your thighs with your palms up
2. With your dominant hand, touch the tip of each finger with your thumb, start with the index finger and move along in order at the rate of about one movement/second
3. Return to the start position. Now imagine the movement, concentrate on the intensity of the sensations.
4. Indicate on the scale the quality of the imagined movement

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(repeat questions 13, 14,15 for the other side)

Question 16

1. Sitting straight, head straight and hands resting on your thighs
2. Bend at the waist, moving your trunk forward as far as possible then straighten up again
3. Return to the start position. Now imagine the movement, concentrate on the intensity of the sensations.
4. Indicate on the scale the quality of the imagined movement

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**Question 17**

1. Sitting straight, head straight and hands resting on your thighs
2. Raise your lower leg of your non-dominant side as close as possible to horizontal then lower it
3. Return to the start position. Now imagine the movement, concentrate on the intensity of the sensations.
4. Indicate on the scale the quality of the imagined movement

   5  4  3  2  1
   as intense as intense moderately Mildly No
   executing the intense intense intense intense sensation
   action

**Question 18**

1. Sitting straight, head straight and hands resting on your thighs
2. Move your foot on your dominant side out to the side about 30 cm (12 inches) then bring it back
3. Return to the start position. Now imagine the movement, concentrate on the intensity of the sensations.
4. Indicate on the scale the quality of the imagined movement

   5  4  3  2  1
   as intense as intense moderately Mildly No
   executing the intense intense intense intense sensation
   action

**Question 19**

1. Sitting straight, head straight and hands resting on your thighs
2. With your non dominant leg tap your toes on the floor three times; about once/second while keeping your heel on the floor
3. Return to the start position. Now imagine the movement, concentrate on the intensity of the sensations.
4. Indicate on the scale the quality of the imagined movement

   5  4  3  2  1
   as intense as intense moderately Mildly No
   as executing intense intense intense intense sensation
   the action
**Question 20**

1. Sitting straight, head straight and hands resting on your thighs
2. Without moving your heel, turn your toes on your dominant side out to the side as far as possible
3. Return to the start position. Now imagine the movement, concentrate on the intensity of the sensations.
4. Indicate on the scale the quality of the imagined movement

```
5  4  3  2  1
as intense as intense moderately Mildly No
executing the intense intense intense sensation
action
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(repeat questions 17, 18, 19, 20 for the other side)
APPENDIX 2
### Working Memory Assessment

**Visuospatial Working Memory**

*Version 1*

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**Verbal Working Memory** (words: pen, car, bank, fish, door, red, tree, song, moon)

*Version 1*

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<td>bank, song</td>
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</table>
**Kinesthetic Working Memory** (start position: feet flat on floors, hands flat on thighs)

1. Extend the unaffected wrist such that the unaffected hand is lifted off the thigh. **WE**
2. Abduct the unaffected arm out to the side **Abd**
3. Lift the palm of the unaffected hand off the thigh. **Palm**
4. Cross both hands at the wrist and center on the lap (can use the unaffected hand **X** to guide the affected side)
5. Slide the unaffected hand forward on the thigh to touch the knee **Fwd**
6. Touch the ankle of the affected side with the unaffected hand **Ankle**
7. Touch the opposite shoulder with the unaffected hand **Shldr**
### Version 1

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