

Motor imagery and sport performance

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Abstract In the present review, how to measure motor imagery ability, brain activity during motor imagery, the benefits of motor imagery practice, and the influence of sensory inputs on motor imagery, are summarized. First, the classification of motor imagery is explained. Many methods have been utilized to evaluate motor imagery ability. For example, questionnaires, mental chronometry, and mental rotation tasks have been used in the psychological approach. Brain activity has been measured utilizing transcranial magnetic stimulation (TMS), functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and electroencephalography (EEG). Some brain regions are activated motor execution in both and motor imagery, including the supplementary motor area (SMA), the premotor cortex (PM) and the parietal cortex. Although motor imagery is done without movement or muscle contraction, sensory input from the periphery interacts with motor imagery. Brain activation during imagery of an action, as assessed by TMS, is stronger when sensory inputs resemble those present during the actual execution of the action. Many studies have provided evidence of the effects of motor imagery practice on basic motor skills and sport performance. Most elite athletes (70-90%) report that they use motor imagery to improve performance, and professional players, as compared to amateurs, utilize imagery practice more often. Many studies have confirmed that motor imagery practice can also be useful not only in sports, but also for improving performance in patient rehabilitation programs.

Keywords : motor imagery, training, brain

Motor imagery is defined as the mental execution of a movement without any overt movement or muscle activation¹⁾. The general concept of motor imagery has been specified utilizing a wide range of terms which include mental imagery, movement imagery, mental practice, imagery rehearsal, visualization, kinesthetic imagery, visuomotor behavioral rehearsal and internal imagery^{1,2)}. Although motor imagery is a subjective experience, many studies over the last several decades, utilizing various points of view, have shown that objective evaluation and analysis of motor imagery is possible. Various aspects of motor imagery have been capably reviewed and should be consulted for an overview of the general approach¹⁻¹¹⁾. In this review we will focus on “objective evaluation of motor imagery”, and additionally describe our recent study on “Influence of afferent input during motor imagery” while paying special attention to the application of motor imagery to sport performance and rehabilitation from injury and disease.

Classification of motor imagery

Imagine that you are kicking a soccer ball. What kind of image comes into your mind? It might be an image of you playing in the field from the viewpoint of a spectator on the stadium. This is called “third person perspective imagery”^{8,12,13)}. On the other hand, you might have the same image that you would have if you were kicking a ball on the ground. This is called “first person perspective imagery”. Motor imagery is also typically separated into two types according to sensory modalities utilized. These categories have been termed “visual motor imagery” and “kinesthetic motor imagery”^{14,15)}. One example of the latter category would be a laboratory setting where subjects were asked to “create an internal representation and feeling of muscles contracting, and not to use a visual approach where one visualizes oneself performing the task” as in the study by Cowley and colleagues (2008)¹⁶⁾. Motor imagery can also be dichotomized into “internal imagery” and “external imagery”¹⁷⁾. In many cases, kinesthetic imagery corresponds closely to first person perspective imagery or internal imagery, and visual imagery to third

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person perspective imagery or external imagery. Only visual information is available for third person perspective imagery. However, first person perspective imagery can become quite complicated. For example, when you imagine you are kicking a ball, you probably have an image that is composed not only of the kinesthetic sensation coming from your leg, but also of the shock of the impact between your foot and the ball as well as visual images of your moving arms and legs, and the ball heading toward the target after the kick. The first person perspective imagery, thus, includes a variety of inputs from different sensory modalities. Many studies have defined kinesthetic imagery as synonymous with first person perspective imagery. Visual imagery is also sometimes further divided into first person visual imagery (a subjective perspective from the person them self), and third person visual imagery (an objective perspective as a third person)^{18,19}. Indeed, brain activity has been shown to be different between kinesthetic imagery and first person visual imagery²⁰. In any case, when motor imagery is under consideration, it is important to clearly define its modality (kinesthetic or visual) and the perspective (first person or third person).

Assessment of motor imagery

Psychological assessment. The ability to perform motor imagery has been assessed with many types of questionnaires². For example, to evaluate the controllability of the motor imagery (CMI) test²¹, subjects were told to imagine a sequence of six movements (e. g. step 50 cm forward on your right leg, bring your left arm 90° to the left side). Subsequently, they were asked to select the final body posture out of five pictures shown. The ratio of correct answers to incorrect was regarded as indicating subjects relative “ability of motor imagery”. Many questionnaires have been developed to test motor imagery ability such as the vividness of motor imagery (VMI) test²², the vividness of movement imagery questionnaire (VMIQ)²³, the sport imagery questionnaire (SIQ)²⁴, the Florida praxis imagery questionnaire (FPIQ)²⁵, and the movement imagery questionnaire (MIQ)^{26,27}.

Another widely used technique for evaluating motor imagery ability is to measure the time that is taken to imagine a movement/action (mental chronometry)^{7,28,29}. Decety and Michel (1989) compared the time spent for graphic movements (e.g. writing a sentence or drawing a cube) executed either actually or mentally, and reported that the time required was similar for actual execution and motor imagery⁷. In general, when the motor imagery could be performed vividly, the time spent for imagery was very similar to that required for the actual execution of the same movement^{2,28}. However, in situations in which motor imagery is difficult, the time spent for imagining tends to be longer.

For example, in the mental rotation task, subjects

looked at a hand positioned in a variety of angles, and were asked to decide, as soon as possible, whether it was the right or left hand. In the case where a rotated hand was presented, the reaction time was longer, probably because the subjects had to rotate the hand being imaged in order to make the judgement³⁰.

Brain activity during motor imagery. Motor imagery is based on the activity of specific neural networks. Many of these areas and pathways have been elucidated by researchers investigating brain activity during motor imagery. Many techniques have been utilized, and include transcranial magnetic stimulation (TMS), functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and electroencephalography (EEG).

TMS studies. TMS is performed by passing a high-current pulse through a magnetic coil placed on the scalp. Compound motor evoked potentials (MEPs) can be recorded from muscles in response to a single suprathreshold TMS pulse delivered to the contralateral primary motor cortex. TMS ordinarily does not activate corticospinal neurons directly. Rather, it activates these neurons indirectly through synaptic inputs^{31,32}. The magnitude of the evoked descending volley depends, among other things, on the level of excitability of the corticospinal tract³³⁻³⁵. The higher the excitability, the larger the MEP amplitude.

During motor imagery corticospinal excitability is raised above the resting excitability level. Kasai and colleagues (1997) demonstrated that the MEP amplitude of the flexor carpi radialis muscle dramatically increased during imagery of wrist flexion³⁶. Subsequent studies confirmed the phenomenon³⁷⁻⁴⁰. Thus, although actual muscle contraction does not occur, the excitability of the corticospinal tract is increased during motor imagery. However, the increase in excitability is smaller than that which occurs during actual movement⁴¹. Corticospinal excitability during motor imagery of a movement follows the temporal changes in muscle activities that occur during the actual execution of the movement³⁸. This increase in corticospinal excitability is only observed in the agonist muscles and not in the antagonist muscles³⁹. Thus, during motor imagery the brain shows activities very similar to those occurring during the actual execution of a movement.

The difference in corticospinal excitability across individuals corresponds closely to differences in the vividness of their motor imagery as assessed by questionnaire. In one study, Fourkas and colleagues (2008) reported that the vividness of motor imagery assessed by questionnaire correlates with MEP amplitude during motor imagery of a tennis stroke⁴². That is, subjects who can imagine a movement more vividly would also show an enhanced corticospinal excitability during motor imagery as compared to subjects with low imagery ability⁴²⁻⁴⁴.

Paired-pulse TMS can assess changes in intracortical

inhibition or facilitation that occur in the primary motor cortex (M1)⁴⁵ as well as cortico-cortical connectivity between two different areas⁴⁶. Thus, both Abbruzzese and colleagues (1999)⁴⁷ and Liepert and Neveling (2009)⁴⁸ observed that during motor imagery of sequential finger opposition or foot dorsiflexion, intracortical inhibition decreased, but intracortical facilitation remained unchanged. These investigators concluded that the enhancement of corticospinal excitability that occurred during motor imagery was caused by disinhibition. However, modulation of intracortical inhibition during motor imagery might also depend on the required tasks⁴⁹. Stinear and Byblow (2004) demonstrated that intracortical inhibition decreased during imagery of an isometric movement, but not during imagery of the phasic pressing of a computer mouse button⁴⁹. In addition, Lebon and colleagues (2012) reported that intracortical inhibition was not modulated during motor imagery of thumb tapping⁴³. Task complexity also affected the changes in corticospinal excitability that occur during motor imagery. Thus, Roosink and Zijewind (2010) demonstrated that the imagery of complex finger tapping increased corticospinal excitability, as compared to that which occurred during the imagery of simple finger tapping⁵⁰.

It might be expected that corticospinal excitability would be differently affected depending on whether the imagery was kinesthetic or visual. Thus, Stinear and colleagues (2006) reported that kinesthetic imagery increased corticospinal excitability, while visual imagery did not⁵¹. However, in some studies corticospinal excitability was increased during visual imagery to the same degree as during kinesthetic imagery^{19,50}.

Brain imaging studies. To elucidate the neural mechanisms underlying motor imagery, brain activity has been assessed by using fMRI and PET. In general, brain activity during motor imagery is similar to that which occurs during motor execution^{1,52-56}. The supplementary motor area (SMA), the premotor cortex (PM), M1, the parietal cortex, basal ganglia and the cerebellum were activated during motor imagery^{1,13,52-67}. The most consistent findings involved activation of the SMA, PM, parietal cortex and cerebellum. These regions clearly play major roles not only in motor execution but also in motor imagery. In addition, these same neural substrates are very likely to be involved in the acquisition of motor skills by motor imagery (e.g. sequential finger tapping)^{1,68}. However, neural activities in many brain regions were lower during motor imagery than during actual movement^{53,62}. Motor imagery has also been implicated in the activation of other brain regions, such as the dorsolateral prefrontal cortex (DLPFC), the superior parietal lobule, and the insula^{13,53,56,63,64}. However, activation of these areas differs across studies.

Guillot and colleagues (2009) compared brain activity between kinesthetic and visual imagery. Kinesthetic imagery yielded more activity in the SMA, PM, cerebellum

and inferior parietal lobule. In contrast, visual imagery led to more activation in the visual cortex⁶⁴.

EEG studies. It is well known that internal and external events result in a change in many frequency bands of ongoing EEG signals. Depending on the nature of the alteration of the waveform, this is referred to as either event-related desynchronization (ERD) or event-related synchronization (ERS)⁶⁹. ERD seems to reflect the activation of cortical areas involved in sensory, cognitive and motor functions. For example, ERD at 7-11 Hz (alpha bands) observed from the skull above the sensorimotor cortex was related to voluntary arm movement⁷⁰. During motor imagery (kinesthetic imagery) of hand movement, ERD of 8-13 Hz (alpha bands) and 14-30 Hz (beta bands) in the contralateral hemisphere was observed⁷¹. ERD in the alpha bands correlated with an increase in corticospinal excitability during motor imagery⁷².

Event-related potentials (ERPs) have also been used in the investigation of motor imagery^{73,74}. ERPs, which are generally averaged EEG waveforms with respect to each event, reflect time-locked changes in brain activity⁷⁵. Naito and Matsumura (1994) measured a negative potential recorded at FCz in response to a visual cue with motor execution, motor imagery or No-go response⁷³. They demonstrated that the amplitude of the negative component was smaller in the imagery condition than in the execution condition. By contrast, the amplitude in the No-go condition was larger than that in the Go condition. The findings of Naito and Matsumura suggest that neural processes involved with motor imagery differ from simple motor suppression.

Role of the supplementary motor area and the premotor cortex. Most studies indicate that the SMA and PM are activated during motor imagery^{1,13,52-67}. Taken together, these findings indicate the SMA and the PM are very likely to be essential parts of the neuronal network involved with motor imagery. Indeed, activity in the SMA and PM during imagery of the fingers, toes and tongue occurred in the area corresponding to each body part. The same corresponding areas were then activated during the actual execution⁷⁶. In addition, activity in the PM correlated with the vividness of motor imagery as assessed by a questionnaire utilizing a 7-point scale⁷⁷.

By contrast, Kasess and colleagues (2008) examined the effective connectivity during motor imagery utilizing fMRI and dynamic causal modeling⁷⁸. Their results led them to suggest that the SMA suppressed activity in the M1. This conclusion indicates that the lack of activation in M1 during motor imagery could be caused by suppression emanating from the SMA⁷⁸. Therefore, the SMA apparently functions not only to generate motor representation but also acts to suppress the M1 during motor imagery in order to inhibit muscle contraction.

Role of the parietal cortex. Sirigu and colleagues (1996) assessed motor imagery ability by using mental chronometry in patients⁷⁹. They reported that a patient with lesions restricted to the parietal cortex underestimates the duration of motor imagery. This result indicates that the parietal cortex plays an important role in the generation of motor imagery⁷⁹.

Single-pulse TMS over the parietal cortex (superior parietal cortex), which can temporarily deactivate neurons in healthy subjects (virtual lesion)⁸⁰, decreased the accuracy of motor imagery⁸¹. In this experiment, to assess the accuracy of motor imagery, subjects were asked to imagine a sequence of hand and arm movements given by verbal instruction, and then asked to tell the investigator the final position of the hand and arm. Subjects answered correctly if they were able to imagine the movements as the instructions progressed. These findings suggest that the superior parietal cortex also has an important functional role in motor imagery.

Recently, cortico-cortical connectivity between parietal and bilateral primary motor cortices was investigated during motor imagery by using a combination of TMS and transcranial direct current stimulation (tDCS)⁸². During motor imagery, anodal tDCS to the parietal cortex increased MEP amplitude, but only from the ipsilateral M1 and not from the contralateral M1. These results suggest that a major role in motor imagery is restricted to the ipsilateral parieto-motor circuitry.

Role of the primary motor cortex. While some researchers found M1 activation during motor imagery^{56,58,66,83}, others did not^{57,59,61,63,65}. This discrepancy might be associated with such factors as the degree of muscle activity, type of tasks, and subjects¹⁰. Kuhtz-Buschbeck and colleagues (2003) investigated brain activity and corticospinal excitability using fMRI and TMS during motor imagery⁶¹. They found a significant enhancement of corticospinal excitability with TMS, but not significant activation in M1 when utilizing fMRI. These findings indicated a possibility that sensitivity for the detection of neural activation, especially in the M1, was higher for TMS than fMRI.

The effect of physical practice on motor performance is higher 30 minutes after practice than right after practice⁸⁴. That is, skill acquisition occurs not only during physical practice but continues after the practice is over. This phenomenon is called “early consolidation”⁸⁵. Early consolidation was also observed 30 minutes after a motor imagery practice⁸⁴. Inhibition of neuronal activity in M1 by continuous theta-burst stimulation (cTBS) immediately after motor imagery practice blocked the early consolidation. These findings suggest that neuronal activity in M1 is involved in the motor learning that accrues from imagery practice.

Role of the spinal cord. It has been reported that motor

imagery did not modulate spinal excitability as assessed by the H reflex^{86,87} or F wave⁸⁸. By contrast, the stretch reflex was augmented during motor imagery^{87,89}. Aoyama and Kaneko (2011) clarified this potential by demonstrating that the amplitude of the stretch reflex was increased during motor imagery of dorsiflexion and plantarflexion, but the amplitude of H-reflex was not altered. Thus, while motor imagery seems to increase the excitability of some spinal reflexes, others are unaffected. At present, an explanation of how imaging affects spinal networks remains elusive.

Development and aging

Several studies have elucidated the effects of development and aging on motor imagery ability. Molina and colleagues (2008) measured motor imagery ability in children using a mental chronometry task²⁹. They found a significant correlation between the time of actual and the imagery of walking in 7-year-old children, but not in 5-year-olds. This indicates that the ability to utilize motor imagery ability likely develops in children of elementary school age. Mulder and colleagues (2007) demonstrated that motor imagery ability in elderly, as assessed by the vividness of the movement imagery questionnaire, was lower than in younger adults⁹⁰. The functional relationship between age and imaging ability is unclear, but it would be useful to determine when the optimal imaging ability is reached and when it begins to decline.

Influence of somatosensory and visual information on motor imagery

Annett (1996) proposed that not only motor execution but also prospective sensory feedback generated by overt action is simulated during motor imagery⁹¹. Indeed, sensory input interacts with motor imagery⁵⁹. Naito and colleagues (2002) demonstrated that the kinesthetic illusion elicited by tendon vibration (proprioceptive input) of wrist extensor was enhanced by motor imagery of wrist flexion. By contrast, motor imagery of wrist extension decreased the kinesthetic illusion.

Actual posture also affects brain activity during motor imagery^{19,92,93}. For example, Vargas and colleagues (2004) demonstrated that corticospinal excitability during imagery of finger-thumb opposition was larger when the actual posture was the same as the imagined hand (congruent) than when it was different from the imagined hand (incongruent)⁹². This result indicates that afferent posture signals which are congruent with imagined actions enhance corticospinal excitability during motor imagery. However, the effect of posture on motor imagery seems to depend on the type of motor imagery (kinesthetic or visual), because posture has been found to affect corticospinal excitability during kinesthetic imagery, but not during visual imagery¹⁹.

In many sports various tools and objects such as balls, gloves, bats, rackets and swords are used. In order to manipulate the objects, tactile information is indispensable. In the imagery of an action with an object, tactile input generated by passively touching an object has been shown to increase corticospinal excitability⁹⁴⁻⁹⁶. Enhancement of corticospinal excitability was not merely stemming from the effect of just holding a ball, since no MEP modulation occurred when there was no motor imagery. Furthermore, when the actual posture was different from the imagined action, tactile input here too did not increase corticospinal excitability⁹⁵. Therefore, these results suggest that corticospinal excitability during imagery with an object is modulated by actually touching an object through the combination of tactile and proprioceptive inputs.

Visual information also influences corticospinal excitability during motor imagery. Sakamoto and colleagues (2009) showed that MEP amplitude during simultaneous observation and imagery of elbow flexion was facilitated compared to that during observation or imagery alone⁹⁷. However, facilitation due to the combination of observation and imagery was not obtained when the participants imagined an action that was out of phase with the observation. Therefore, congruent visual input with imagined action enhances corticospinal excitability during motor imagery. The above information indicates that sensory input that resembles that produced during the real execution of an action is much more effective in enhancing the process of motor imagery, irrespective of sensory modality.

Improvement of motor skill or performance with motor imagery

Motor imagery practice is useful for both athletes and patients in the acquisition of not only motor skills³, but also muscle strength⁹⁸ and joint flexibility⁹⁹. There is much positive evidence on the effect of motor imagery practice on basic motor skills and performances^{3,8,68,98-105}. Pascual-Leone and colleagues (1995) reported that mental practice (motor imagery practice) of sequential finger tapping for 5 days reduced temporal errors⁶⁸. In addition, Allami and colleagues (2008) demonstrated that the time required for the visuomotor task of grasping an object and inserting it into a slot was improved over 240 trials of motor imagery practice¹⁰⁴. Motor imagery (kinesthetic or first person imagery) practice in a multiple-target arm-pointing task, which required both speed and high spatial accuracy, shortened the time period from the 'start' to the 'end' of the motion¹⁰⁵. Interestingly, the time decreased trial-by-trial through the process of 60 trials. Amemiya and colleagues (2010) reported that the motor imagery practice of finger tapping improved not only the trained hand but also the untrained hand. Thus, it was shown that the effect of motor imagery practice can also affect the untrained hand¹⁰⁶.

Muscle strength of a fifth finger abduction over a four

week period was increased by training with motor imagery without any muscle activation⁹⁸. However, the ratio of the enhancement of muscle strength was smaller in the motor imagery training (22%) than in the execution training (30%). Since muscle hypertrophy had not occurred during motor imagery practice, the enhancement of muscle strength was likely to have been related to plasticity in the central nervous system⁹⁸.

Five weeks of motor imagery practice involving stretching exercises (e. g. stretching the hamstring, shoulder and ankle muscles) enhanced joint flexibility in relation to both active and passive stretching of the hamstring and ankle muscles⁹⁹. As might be expected, an understanding of the mechanism whereby this enhancement of joint flexibility came about remains obscure.

Motor imagery practice of big toe abduction did not increase the range of motion for subjects that were unable to perform the movement¹⁰³. However, subjects who were able to perform the movement did show an increased range of motion.

By contrast, Kaneko and colleagues (2003) investigated modulation of M1 activity during motor imagery after immobilization of an upper limb¹⁰⁷. Corticospinal excitability during motor imagery was decreased by immobilization and there was no modulation of the M-max and H-reflex. This would indicate that disuse of a limb attenuates the neural processes that are involved with motor imagery at the cortical level.

Motor imagery in sports

Several studies showed enhancement of sport performance with motor imagery practice^{3,8,100,101,108}. For example, Isaac (1992) demonstrated that 6-week training sessions with actual practice and motor imagery of trampolining (e.g. rotation or twist) improved the skill of the actual movements, as assessed by five nationally qualified judges, in the training group compared to the control group (no motor imagery)¹⁰⁸. The effect of motor imagery practice was weaker than that of actual motor practice^{68,98,104}. However, motor imagery practice could well become a supplementary training measure to improve overall performance in athletes.

Most elite athletes (70-90%) report that they use motor imagery for improving their sport performance. In addition, professional players of basketball, football, gymnastics, volleyball, dance, and swimming, perform motor imagery practice more often than amateurs¹⁰⁹. In gymnastics, elite athletes perform first person imagery (internal imagery) rather than third person imagery (external imagery)¹⁷.

Roure and colleagues (1999) noted that motor imagery quality can be estimated by monitoring the modulation of autonomic responses during motor imagery of volleyball¹¹⁰. The magnitudes of changes in skin potential, skin blood flow, heart rate and respiratory frequency during

motor imagery correlated positively with performance improvement. In the previously mentioned study of trampolining, subjects who had a high ability in motor imagery, as assessed by the vividness of a movement imagery questionnaire, showed a greater performance improvement than the subjects with low imagery ability¹⁰⁸). Since modulation of corticospinal excitability during motor imagery reflects the ability of motor imagery, measurement of corticospinal excitability would be an appropriate objective methodology for estimating the effect of motor imagery practice. However, little is known why some individuals are quite different in their motor imagery abilities.

Little is known about brain activity during motor performance in athletes, either during performances or during motor imagery¹¹¹). In one of the few studies in this area, Fourkas and colleagues (2008) investigated the modulation of corticospinal excitability with TMS during imagery of the forehand stroke of novice and expert tennis players. In the expert players, corticospinal excitability increased during imaging of the action, but not during the imaging of a golf drive or a table tennis forehand stroke⁴²). The excitability in novices was not modulated by any of the three actions. Thus, modulation of corticospinal excitability during imagery of complex movements would appear to be influenced only when the motor repertory or performance level is relatively sophisticated. Another study compared the brain activity of athletes and novices. One finding was that during motor imagery of a high jump, the premotor cortex area and cerebellum were activated in high jumpers, while visual areas (e.g. the superior occipital cortex) were activated in novices¹¹²).

Conclusion

In the present review, we summarize many areas. These include the benefits of motor imagery practice, measurements of motor imagery ability, brain activity during motor imagery, and influence of sensory inputs on motor imagery. Motor imagery is useful for acquiring motor skills, and can be objectively evaluated with behavioral and neurophysiological methods. The brain regions that are important for motor execution show activation during motor imagery as well. Brain activation during the imagery of an action is stronger when sensory inputs are similar to those that occur during the actual execution of the same action. It is still unclear about why there are motor imagery differences that relate to the ability of athletes as compared to non-athletes, or to the individual differences in the ability to create vivid motor imagery. These differences are interesting topics for further study.

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