Cognitive Neuroscience

ISSN: 3035-062X
2024, 1(2)

Preliminary Reports and Negative Results in Life Science and Humanities

Motor Imagery in the Primary Motor Cortex: A preliminary review

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Citation: Riggio F., Gangemi A. (2024). Motor Imagery in the Primary Motor Cortex: A preliminary review. Preliminary Reports and Negative Results in Life Science and Humanities 1(2). https://doi.org/10.13129/3035-062X/prnr-4651

Abstract

Understanding the role of motor cortex (M1) in motor imaginary (MI) is an interesting area of research for the treatment of pathological conditions affecting motor execution. For this reason, in this preliminary review, we examine the literature on the role of M1 in MI. In particular, we review studies that have used brain imaging and non-invasive brain stimulation techniques to investigate M1 activation during MI tasks. Since the literature on this topic is quite inconsistent, in the present paper we distinguish between two lines of research: studies that confirm M1 involvement in MI and research that show that there is no M1 activation during tasks of MI. In addition, studies on neurological disorders and age differences related to the connection between MI and M1 are reviewed.

Keywords: Primary motor cortex; Motor imagery; Neural substrates; Neurological disorders

Introduction

Motor imagery (MI) is the cognitive process that defines the ability to mentally represent a movement in the absence of a concrete and real motor execution. It involves internal representations of motor actions and actions that inhibit movement (Jeannerod, 1994; Decety, 1996; Guillot et al., 2012).

According to the literature, MI includes a kinesthetic form (KMI), which refers to the imagination of proprioceptive sensations elicited by the action and involves sensorimotor areas, and a visualisation form (VMI). It involves visualising the movement both from an internal perspective (what is seen when a movement is performed) and from an external perspective (as if the subjects were watching themselves) (Jeannerod, 1994; Stevens, 2005; Munzert, 2009). MI is thus a complex and crucial cognitive process. However, there are still many theoretical divergences regarding its role and neurobiological circuits.

Several theories attempt to define MI and the neurobiological processes involved. For example, the Motor Simulation Theory (MST) (Jeannerod, 2001), the Motor Emulation Theory (MET) (Grush, 2004), the Motor-Cognitive Model (MCM) (Glover & Baran, 2017), the Perceptual-Cognitive Model (PCM) (Frank & Schack, 2017) and the Effects Image Model (EIM) (Bach et al., 2012). These theories address the phenomenon by describing its complexity and the goal it serves. For example, some theories propose that occurs even before the planning of motor execution. In terms of goals, almost all theories agree that the motor execution plan is the final end of this process, while others suggest that the goal is to remember the desired effects of the action. Finally, others hypothesis that MI is aimed at predicting errors resulting from a potential motor action (for a detailed review see Hurst et al., 2022 and Rieger et al., 2023).

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From a neurobiological point of view, the cerebral structures involved in MI are connected to different cortical and subcortical areas. Brain imaging techniques have shown that the areas involved are similar to those activated during actual movement execution, in particular the primary motor cortex (M1), the supplementary motor area (SMA), the premotor cortex (PM), which regulates movement planning, the parietal cortex and the posterior cerebellum (Hétu et al., 2013; Hardwick et al., 2018). Therefore, MI and movement share brain regions that are active during both motor execution and mental imagery.

The role of M1 during movement execution is obvious. M1 is located in Brodmann area 4 in the precentral gyrus of the frontal lobe. Betz cells have been found in this area - pyramidal cells involved in the pyramidal tract that innervate other subcortical structures such as the brainstem. The motor cortex receives subcortical thalamic afferents that are closely linked to motor information for voluntary movement execution (Pearson, 2000). The executive function of M1 is supported by many studies. A direct relationship has been found between muscle strength and frequent stimulation of neurons in M1, as well as rapid movement execution following electrical and magnetic stimulation of the area (Levy et al, 1984; Mills, 1991; Facchini et al, 2002).

However, the role of M1 appears to be controversial. The degree to which neural circuits are activated during motor imagery and movement execution suggests that M1 plays a central role in both processes, although the degree of involvement remains a topic of ongoing investigation. For example, Pascual-Leone et al (1995) showed that M1 is stimulated during motor learning through MI training, resulting in improvements in motor execution, whereas Sharma et al (2006) showed strong activation of motor areas during motor imagery tasks, but weak and inconsistent activation of M1 in healthy subjects.

Since MI involves the activity of motor areas, is it necessary to inhibit motor commands to prevent movement execution? What then is the role of M1 during MI?

Given the complexity of the topic, in this narrative review we will attempt to answer these questions by examining the studies that have investigated the role of M1 in MI processes.

In particular, we explore the relationship between motor imagery and M1 by critically reviewing the existing literature, highlighting key findings, and providing insights into how M1 actually contributes to motor imagery.

Role of M1 in MI: empirical studies

The following is a review of studies that primarily aimed to investigate the involvement of M1 during motor imagery tasks. In addition, this review includes studies that, although having a different primary aims, reported findings of interest in explaining how and if motor imagery activates cortical and subcortical areas, including M1.

All reviewed studies used brain imaging techniques and non-invasive stimulation methods. The experiments typically involve motor imagery tasks in which participants are asked to imagine the movement of a limb or a more complex movement.

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The samples examined include healthy people, the ageing population, people with neurological conditions, or people with an amputated limb.

The review is organized by grouping studies that found no relationship between MI and M1, and those that found a relationship.

Studies not involving M1 in MI

This section reviews studies that have found involvement of cortical areas other than M1 during MI tasks. These findings suggest that the areas activated by MI are basic motor areas, but are not directly involved in motor execution because they are inhibited.

For example, McInnes and colleagues (2015) collected 23 studies in a meta-analysis and found that lesions in the posterior frontal lobe, where Brodmann area 4 is located, do not impair MI abilities. Similarly, Hardwick et al. (2018) showed that during both MI and actual movement execution, the brain areas involved are numerous, but specifically, MI recruits posterior regions of the cingulate cortex associated with cognitive control, whereas movement execution involves anterior regions associated with basic motor functions. Later empirical studies have shown similar results.

Moreover, in a study by Maegherman and colleagues (2019), 20 participants were asked to perform motor execution tasks as well as MI tasks involving the muscles of the lips and hands. Using motor evoked potentials (MEPs), no involvement of M1 was found during the proposed MI tasks.

In addition, Barhoun and colleagues (2022) investigated M1 involvement during hand rotation and letter and number rotation tasks in a sample of young right-handed adults with typical and atypical motor skills. Non-invasive stimulation techniques were applied to M1 and SMA. The study did not provide sufficient data to establish a causal or direct relationship between M1 and MI. Instead, M1 and SMA were stimulated by motor input, but not by imaginative input. However, some studies have shown that the SMA plays an inhibitory role on M1 activity to prevent muscle contraction during imagery (e.g.: Solodkin et al., 2004; Confalonieri et al., 2012; Yoo et al., 2020; Solomon et al., 2021).

Furthermore, Kasses and colleagues (2008) suggested that the lack of M1 activation during MI may be due to this inhibitory function of the SMA. In terms of movement inhibition during MI tasks, Chen and colleagues (2021) also demonstrated inhibition of mu oscillations (8-13 Hz), which are present in the motor cortex and are related to both motor execution and comprehension, during MI tasks.

Different results: empirical evidence for M1 activation during MI

Below is a selection of different results from the studies presented in the previous paragraph. Indeed, M1 activation is highlighted and its involvement is considered as part of MI. Studies on areas of the literature such as the role of synaptic plasticity in M1, age differences and the role of MI in the treatment of some neurological diseases will also be presented.

First of all, regarding the activation of M1, it seems that kinesthetic information activates M1 more strongly than the visualization form, by constructing a neural representation of the imagined movements (Stinear et al., 2006; Ruffino et al., 2017).

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The study by Roth and colleagues (1996) used functional magnetic resonance imaging (fMRI) in healthy right-handed subjects to investigate M1 involvement during a right or left thumb-finger opposition task, performed both physically and imaginatively. Four out of six subjects showed significant M1 and premotor cortex involvement during MI. Moreover, other studies have shown M1 involvement during hand movement imagery (Lotze, et al., 1999; Lacourse, et al., 2005).

Using fMRI, Rodríguez and colleagues (2004) investigated the role of M1 in four tasks, including a motor task, an MI task and another motor task combined with a mental arithmetic task. The results confirmed the role of M1 not only in actual movement performance, but also during MI and motor performance tasks with distractors. Similar results were obtained in the study by Makary and colleagues (2017), who examined differences in the intensity and activation of specific brain areas during both motor execution tasks and MI tasks involving facial muscle engagement in 41 volunteers. Before undergoing fMRI, participants took part in a training session in which they alternated between motor execution and MI. The results showed M1 involvement during MI tasks.

Furthermore, Lorey and colleagues (2013) found activation in the premotor cortex, supplementary motor cortex, inferior frontal gyrus and M1 of both hemispheres using motor tasks, movement observation and MI when participants were asked to imagine motor sequences involving repetitive movements of the hand and foot. Similar results were found by Munzert and colleagues (2008), who demonstrated the involvement of M1 in MI using MI tasks involving athletic movements, confirming its activation.

The role of M1 in MI has also been investigated in language tasks. For example, Tomasino and colleagues (2007) investigated whether M1 involvement in word processing arises from the semantic representation of the words themselves, or whether M1 activation depends on participants' strategy of simulating movements while reading. Participants were asked to silently read short sentences about a motor scene. In a subsequent task, they were either asked to imagine a situation or to identify the letters of the sentences they had just read. These different tasks allowed the researchers to show that imagining motor scenes affects neural activity in M1.

In addition, other studies using non-invasive brain stimulation (NIBS) techniques have confirmed that language processing, in particular the learning of semantic associations related to motor skills, leads to changes in the motor cortex where action mappings are represented (Candidi, et al., 2010; Vicario, et al., 2013).

MI and Synaptic Plasticity in M1

In M1, synaptic plasticity is a fundamental mechanism by which motor skills are learned and refined, and it plays a crucial role in motor recovery after injury. Research has shown that MI can induce changes in M1 similar to those induced by physical exercise. For example, Bonassi and colleagues (2017) confirmed the involvement of M1 in MI tasks by investigating this process in combination with peripheral nerve stimulation to modulate synaptic plasticity in M1. An experimental group was asked to mentally execute a finger movement following an auditory cue, while simultaneously receiving stimulation. Two control groups either physically performed or imagined the same number of finger movements in response to the auditory input. Performance was assessed before and after MI training and at a follow-up visit. The results showed that training combining MI

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with auditory input affected motor performance by activating plasticity mechanisms in M1, similar to motor execution. Analogously, Bonassi and colleagues (2020) confirmed in their experiment that MI tasks can stimulate motor learning by inducing neuroplasticity in M1.

Confirming the benefits of motor learning through MI, Avanzino and colleagues (2015) investigated the plasticity induced in M1 by MI tasks. Specifically, participants were instructed to perform and visualize a sequence of finger movements as quickly as possible. The results of the study highlighted the role of motor areas, particularly M1, in motor learning through imagery, which modulates synaptic activity in these areas more than physical practice. Debarnot and colleagues (2021), in a study of 14 healthy participants, used MI tasks on an immobilized limb to investigate the effects of MI on M1 and the characteristics of plasticity. The results showed that MI was effective in activating M1 and preventing the reduction in activity caused by the immobilised limb. The authors therefore hypothesise that MI may be useful for activating M1 and may be used to counteract the loss of motor function, as it exploits the mechanism of synaptic plasticity.

MI, M1 & Aging

The study of the relationship between MI and M1 has also included the elderly population. Motor control, balance and posture are not immune to changes across the lifespan. Sharma and colleagues (2014) investigated the effects of ageing on the organization of the M1 through MI and movement execution tasks. The results demonstrate the role of the M1 during MI in older adults, although these individuals have reduced MI abilities. Similar findings were obtained when the brain regions involved in maintaining balance and posture were examined (in both adult and elderly subjects). The cortical areas involved are the same as those activated during movement execution, including M1. Furthermore, it appears that there are differences between older adults and younger people, since with age there is increased activity in the SMA and M1 during MI. This finding is explained by various hypotheses related to theories of brain ageing (for further reading, see Allali et al., 2014; Mouthon et al., 2018).

Contrasting results were found in a recent study by Yu and colleagues (2024), who investigated HbO2 levels in both adults and elderly people. HbO2 is an indicator of brain tissue activity and function, and its regulation is essential for maintaining normal alertness and cognitive function. In older adults, the level of this indicator was found to be elevated in M1 during motor execution tasks and passive motor tasks (e.g. when the examiner moved the subject's elbow without requiring voluntary motor execution), but not during MI tasks. Similarly, the results of Wang and colleagues (2014) showed greater activation of the sensorimotor cortex and cerebellum during MI in older adults, although M1 was still activated, especially in the left hemisphere.

MI and M1: neurological disorders

In neurological disorders, MI plays an important role in the recovery of motor function in many disorders. The following studies focus on the recovery of motor execution through MI tasks, exploiting the plasticity of the brain mentioned above.

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In one study (Debarnot et al., 2011), participants learned a finger tapping sequence first through MI and then through physical practice. In both groups, the training was equally effective and led to an early improvement in motor performance. This conclusion was later confirmed by the results of an additional control group, in which the authors demonstrated that M1 plays a causal role in the motor improvement induced by MI training. Makary and colleagues (2017) confirmed these findings and also showed that M1 involvement in MI facilitates learning even at rest.

Another study (Saruco et al., 2017) investigated the benefits of MI training for postural recovery tasks in combination with anodal transcranial direct current stimulation (tDCS) applied to M1. The results showed improved motor performance when participants were exposed to both training and stimulation. In addition, eighteen healthy right-handed adults underwent MI training combined with tDCS over M1, and plasticity effects in M1 were observed. The positive results demonstrated the usefulness of MI techniques for motor performance and established a relationship between M1 and MI, particularly when considering the potential treatment of neurological disorders, with M1 identified as a potential target for future interventions (Foerster et al., 2013; Hong et al., 2012). For example, to promote recovery from stroke, MI is a training method that provides an additional source of information compared to movement execution. In stroke patients, recovery of motor function occurs through stimulation of M1. This stimulation can also be facilitated by MI tasks, which activate cortical motor areas such as M1 and play a non-executive role in action (Sharma et al., 2009).

Another area of investigation for therapeutic treatments concerns limb amputation. In his review, Hugdal (2001) shows that in subjects with an amputated limb, MI activates the same areas involved in movement execution, including M1. In addition, MI is also able to activate the primary sensorimotor cortex in relation to pain imagery. Similarly, in a study by MacIver and colleagues (2008) in subjects with upper limb amputations, MI tasks led to altered activity in M1 following nervous system injury, providing evidence for M1 involvement in MI.

M1 activation during MI may also be important in a neurodegenerative condition such as Parkinson's disease (PD). This neurological disorder is a neurodegenerative condition that primarily affects the motor system. It is caused by the progressive loss of neurons in the substantia nigra, leading to a gradual dopaminergic deficit in the striatum. In addition, other biomarkers, such as α-synuclein aggregates, characterize the disease (for a comprehensive review, see Poewe et al., 2017). The symptomatology of PD, at least in the early stages, is characterized by motor deficits. Therapeutic treatments should focus on restoring or maintaining motor function in this patient population. Studies in the literature confirm that MI involves the motor execution centers and that in PD patients this process abnormally activates certain areas, making it less lateralized, with predominant activation of the SMA, the extrastriate body area and the occipito-parietal cortex (Thobois et al., 2000; Samuel et al., 2001; Helmich et al., 2007).

Another area of scientific research related to M1 and MI is spinal cord injury (SCI), which is one of the leading causes of long-term disability. SCI is a neurological condition that affects multiple body functions and organ systems (Maynard, et al, 1997). The involvement of M1, as well as motor and pre-motor areas, in the perception of pain experienced by these patients has been discovered (Henderson et al., 2006). For therapeutic purposes, the use of MI for imagining movements of immobilized body parts has been investigated in this population. The results are conflicting: in some cases activation of M1 appears to increase pain during MI tasks, while in other cases overlapping

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activation of motor areas has been observed, with M1 being activated in some cases and not in others (Enzinger et al., 2008; Gustin et al., 2008; 2010; Kumari et al., 2022).

Discussion

The role of the primary motor cortex (M1) in motor imagery (MI) is not well defined. The areas activated during MI and motor execution are similar and include other regions such as the premotor cortex, supplementary motor area (SMA) and parietal areas, all of which are involved in the mental simulation of movement. The premotor cortex, which is responsible for the planning and preparation of motor actions, is thought to interact with M1 during MI to coordinate the "mental execution" of the movement. Similarly, the SMA is involved in the internal generation of movement and may contribute to the initiation of MI, particularly in more complex or novel movements. The parietal cortex, which processes sensory and proprioceptive information, may play a key role in integrating sensory feedback during MI. The involvement of these regions suggests that MI relies on a dynamic and distributed network rather than a single motor representation in M1. Furthermore, the putamen, basal ganglia, cerebellum, and premotor and somatosensory regions are involved in MI as they are responsible for motor preparation, although they are less involved during execution (Hardwick et al., 2018). Both motor execution and MI involve the planning and execution of the same motor plan, but in the latter case there is a mental representation of the action in the absence of movement. In this context, behavioural studies and brain imaging have shown that the cortical areas activated during MI are common to those involved in planning and execution (Hanakawa et al., 2003). However, the exact role of M1 during MI remains controversial due to inconsistent results. Given that the primary role of M1 is motor execution, it is difficult to understand how MI, which involves movement inhibition, could involve M1.

This review summarizes studies investigating the role of M1 in MI, some of which provide evidence for its involvement, while others provide insufficient evidence to support its involvement. It also discusses research demonstrating the benefits of MI practice, particularly in rehabilitation contexts, where motor learning via MI is mediated by M1 and improves motor performance even in patients with neurological conditions.

In this scenario, NIBS techniques have proven to be important in clarifying the role of M1 in MI. NIBS techniques such as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS) have provided evidence that M1 may be involved in the cognitive process of MI. In addition, M1 activation has been observed by recording event-related potentials (ERPs) during simple motor performance and imagery tasks (Carrillo de la Peña et al., 2008).

What could be the source of these conflicting results? One challenge lies in the variety of methods and procedures used in the studies available in the scientific literature. Although many studies have used fMRI or transcranial magnetic stimulation (TMS) to investigate the role of M1 in MI, the MI tasks that participants perform are often heterogeneous. In addition, most studies have had very small sample sizes, often less than 20 participants. There are also few studies in healthy populations, and those in pathological populations tend to focus on rehabilitation training. These differences complicate the synthesis of results and call for a more standardized approach to studying MI and its relationship with M1 (Lotze et al., 2006; Grosprêtre et al., 2016). Future research should aim to better

ISSN: 3035-062X
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define the role of M1 in MI, particularly in the context of rehabilitation and motor learning, and explore how this process can be harnessed for therapeutic benefit.

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2024, 1(2)
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