

SIMILARITIES IN BRAIN ACTIVITY DURING MOTOR IMAGERY AND MOTOR EXECUTION: A LITERATURE REVIEW

SIMILITUDES EN LA ACTIVIDAD CEREBRAL DURANTE LA IMAGINERÍA MENTAL Y LA EJECUCIÓN MOTORA: UNA REVISIÓN DE LITERATURA

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Abstract

The aim of this study was to systematically review and analyze the evidence on Motor Imagery (MI) and Motor Execution (ME) brain activity, comparing the number of active brain regions, activation frequency, and relative activation differences between conditions. A literature search was conducted across eight databases with the final search in September 2024. Studies were included if they involved healthy participants of any age, assessed neural activity in at least one brain region during MI and ME of a motor skill, using EEG, fMRI, NIRS, or PET. The Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies was used to assess risk of bias. Analyses focused on the frequencies for the brain areas reported as active during both conditions. Eighteen studies ($N = 313$) were included, with 67% using fMRI. No significant difference ($W = 36.00$; $p = 0.122$) was found in the number of brain areas activated between ME ($M = 6.44 \pm 3.65$) and MI ($M = 5.56 \pm 4.31$). Four Brodmann areas (BA1, BA4, BA6, BA40) and the cerebellum were consistently activated in both conditions. The findings highlight substantial neural overlap between ME and MI, particularly in BA1, BA4, BA6, BA40, and the cerebellum, supporting the functional equivalence hypothesis of MI and ME.

Keywords: Activation, brain regions, mental practice, motor control, motor learning.

Resumen

El objetivo de este estudio fue analizar sistemáticamente la evidencia sobre la actividad cerebral de imaginación mental (IM) y la ejecución motriz (EM), comparando el número de regiones cerebrales activas, la frecuencia de activación y las diferencias relativas de activación entre condiciones. Se realizó una búsqueda bibliográfica en ocho bases de datos con la búsqueda final en septiembre de 2024. Los estudios se incluyeron si incluían participantes sanos de cualquier edad, evaluaban la actividad neural en al menos una región cerebral durante la IM y la EM de una habilidad motora, mediante EEG, fMRI, NIRS o PET. Se utilizó la "Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies" para evaluar el riesgo de sesgo. Los análisis se centraron en las frecuencias de las áreas cerebrales indicadas como activas durante ambas condiciones. Se incluyeron 18 estudios ($N = 313$), de los cuales el 67% utilizó fMRI. No se encontraron diferencias significativas ($W = 36,00$; $p = 0,122$) en el número de áreas cerebrales activadas entre EM ($M = 6,44 \pm 3,65$) e IM ($M = 5,56 \pm 4,31$). Cuatro áreas de Brodmann (BA1, BA4, BA6, BA40) y el cerebelo se activaron de forma consistente en ambas condiciones. Los hallazgos indican un solapamiento neural sustancial entre la EM y la IM, particularmente en BA1, BA4, BA6, BA40 y el cerebelo, apoyando la hipótesis de equivalencia funcional de la IM y la EM.

Palabras clave: Activación, aprendizaje motor, control motor, práctica mental, regiones cerebrales.

Introduction

Motor imagery (MI), also known as mental imagery, is the voluntary and active process of internally representing or replaying a movement within working memory. In contrast, motor execution (ME) involves overt movement (Hanakawa, 2016; Matsuo et al., 2020; Wriessnegger et al., 2008). Scientific evidence has shown that MI and ME activate similar brain regions (Hanakawa, 2016; Héту et al., 2013; Jackson et al., 2003; Lee et al., 2019; Lotze et al., 1999; Matsuo et al., 2020; Nakano, 2012).

Historically, researchers in motor learning and control relied on behavioral measures to infer brain activity (Magill & Anderson, 2017). However, advances in technology have enabled the use of various techniques adapted from clinical settings, such as electroencephalography (EEG), positron emission tomography (PET), functional magnetic resonance imaging (fMRI), and others, to assess brain activity during MI and ME (Formaggio et al., 2010; Héту et al., 2013; Jackson et al., 2003; Lacourse et al., 2005; Lotze et al., 1999; Magill & Anderson, 2017; Zich et al., 2017).

Several studies have reported activity in primary motor cortex, presupplementary and supplementary motor areas, primary somatosensory area, medial orbitofrontal cortex, dorsolateral prefrontal cortex, superior and inferior parietal cortex, posterior parietal cortex, inferior frontal gyrus, supramarginal gyrus, lingual gyrus, basal ganglia, thalamus, putamen, and cerebellum during ME (Héту et al., 2013; Jackson et al., 2003; Lee et al., 2019; Matsuo et al., 2020; Nakano, 2012; Wang et al., 2014) for different movements including grasping (Filimon et al., 2007), chopstick and hammer handling (Nakano, 2012), finger tapping (Macuga & Frey, 2012), self-feeding activity (Matsuo et al., 2020), and foot sequences (Jackson et al., 2003). Moreover, some studies had reported that similar brain areas were activated during MI (Di Nota et al., 2016; Héту et al., 2013; Lee et al., 2019; Matsuo et al., 2020; Nakano, 2012; Wang et al., 2014; Zich et al., 2017). Most of the areas with similar activation during MI and ME include the primary motor cortex, supplementary motor area, premotor cortex, primary somatosensory cortex (Wang et al., 2014).

Several factors may moderate the brain activity during MI, such as the type of MI (kinesthetic versus visual) (Neuper et al., 2005), the age of the participants (Wang et al., 2014; Zich et al., 2017), and the type of motor task (Nakano, 2012). For example, kinesthetic MI has been associated with higher activity rates than visual MI, with the sensorimotor hand area showing more activity during kinesthetic MI, whereas visual MI does not report clear activity (Neuper et al., 2005). Differences in intensity and areas activated have been found between young and older adults; the precentral gyrus during MI is more active in younger adults, while the putamen and angular gyrus show stronger activation during MI in the older adults (Wang et al., 2014). Additionally, during MI event-related desynchronization (ERD%) and deoxyhemoglobin concentration (HbR) are less lateralized in older adults compared to younger adults (Zich et al., 2017).

Although numerous studies have demonstrated that MI and ME activate overlapping brain regions, the extent of their similarity remains debated. Some findings suggest a strong functional equivalence between MI and ME (Jackson et al., 2003; Lee et al., 2019; Lotze et al., 1999; Matsuo et al., 2020; Nakano, 2012), while others report key differences (Di Nota et al., 2016; Zich et al., 2017) that may indicate partially independent mechanisms (Macuga & Frey, 2012). However, previous studies have varied in methodologies, task types, and participant characteristics, making it difficult to draw consistent conclusions. Additionally, while it is known that factors such as MI type (kinesthetic vs. visual) and age influence brain activity during MI, their impact on MI-ME similarities has not been systematically analyzed. A clearer understanding of these similarities and differences is crucial, as MI is increasingly used in rehabilitation, skill acquisition, and brain computer interfaces.

Therefore, this study aims to systematically summarize and analyze the scientific evidence on similarity of brain activity while performing motor imagery (MI) and motor execution (ME). Specifically, the analysis will: (1) compare the number of brain areas reported as active in each condition, (2) assess the frequency of activation reported for each brain area, and (3) determine whether specific brain areas show greater activation in ME or MI.

Methods

Identification of Studies and Search Strategy

A comprehensive literature search for potentially eligible studies was conducted at Scopus database. The following keywords were used for the search: ("motor imagery") AND ("motor learning" OR "motor performance" OR "skill acquisition" OR "motor skill performance" OR "motor execution") AND ("brain act*" OR "fMRI" OR "EEG" OR "PET" OR "NIRS") NOT (automobiles OR cars OR vehicles). Filters used included scientific papers, scientific journals, and no other limits were used. Additionally, the reference lists of retrieved articles were manually reviewed to identify relevant research. The first search was conducted in June 2023; while the final search was conducted in September 2024.

Study Eligibility Criteria and Selection Process

Included studies met the following criteria: (1) the study sample involved healthy participants of all ages, (2) the study assessed neural activity in at least one specific area during motor imagery and motor execution of a motor skill, using EEG, fMRI, NIRS, or PET. One author screened by title and abstract in the first step of the selection process, while two authors screened full-text records in the second step independently and consulted the third author to resolve any differences.

Data Extraction

Two authors extracted the data from the included papers capturing study characteristics (year of publication, country, study design), sample characteristics (sample size, age, sex), assessment method (fMRI, PET, EEG), type of MI (visual, kinesthetic), and principal results (brain areas reported as activated, without considering laterality). Data extraction was obtained independently and consulted the third author to resolve any differences.

Risk of Bias

The Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies was developed by the National Institute of Health (NIH) of the United States of America, it includes 14 questions with (Yes/No) answers. The questions are related to the research question, study population, sample eligibility and size, characteristics of the exposure to treatment, outcome measures, blinding, follow-up rate, and statistical analyses (available at). One author extracted the information.

Outcome Variables

The primary outcome variable was brain activity defined as the increase in electrical signals or blood flow throughout cortical regions (Kandel et al., 2012; Purves et al., 2013). This activity can be assessed with various instruments, including functional magnetic resonance imaging (fMRI), positron emission tomography (PET), functional near-infrared spectroscopy (fNIRS), and electroencephalogram (EEG). The fMRI is sensitive to increases in blood flow and detects fluctuations in oxygen levels, known as blood oxygenation level-dependent (BOLD) signals (Lee et al., 2019; Wang et al., 2014). The fNIRS measures cortical changes in the concentration levels of oxygenated hemoglobin (oxyHb), deoxygenated hemoglobin (deoxyHb) and total hemoglobin with OxyHb being the most sensitive indicator of changes in regional cerebral blood flow (Nakano, 2012). The PET reflects metabolic activity in brain areas, associated with neural activity through glucose consumption (Stephan et al., 1995). EEG captures waves patterns (characterized by frequency and amplitude) of neuronal electrical activity (Kandel et al., 2012), represented as event-related desynchronization (ERD) and event-related synchronization (ERS) (Neuper et al., 2005). For this review it was coded and analyzed the frequency the BA was reported as activated.

Data Analysis

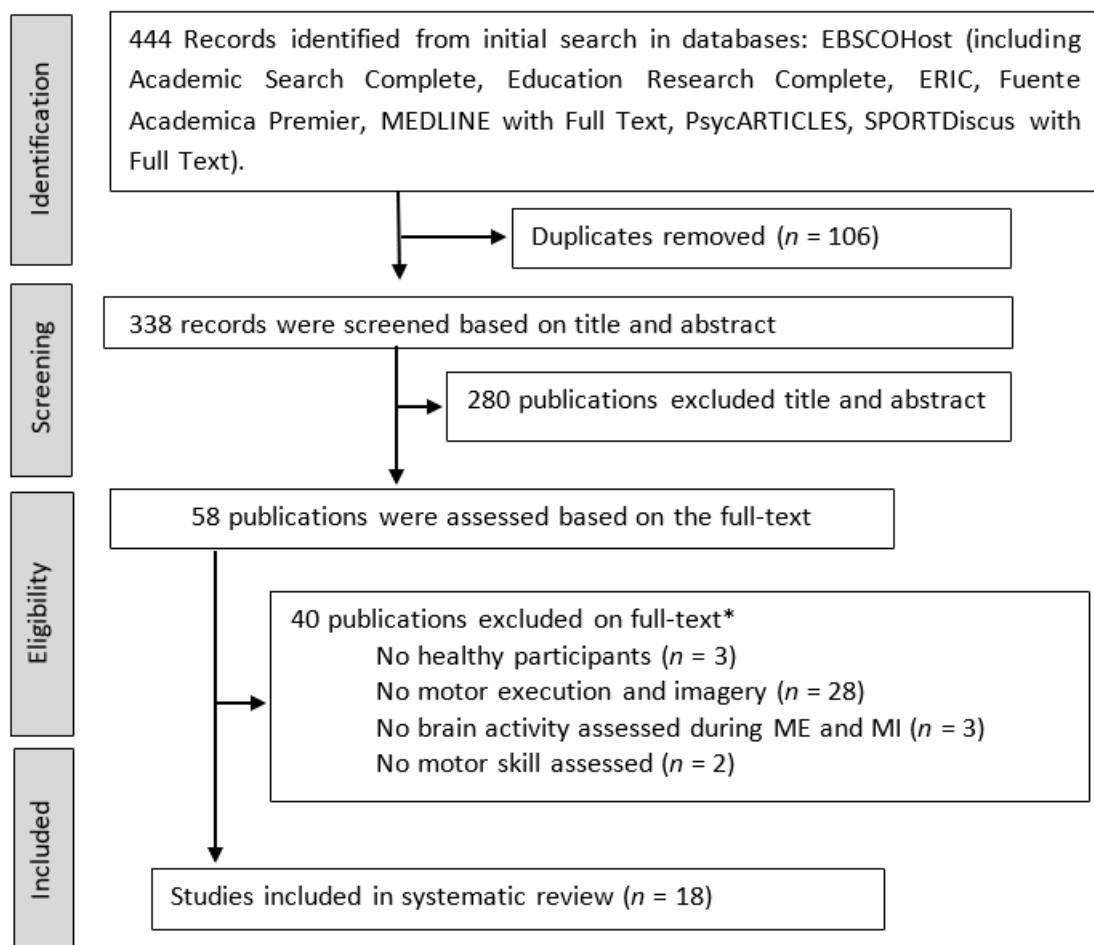
All data was coded based on Brodmann's area. Descriptive statistics were calculated, including absolute and relative frequencies for the brain areas reported as active during ME and MI. Additionally, the studies were categorized based on whether they reported all possible brain areas activates or assessed specific regions of interest (ROI). To assess similarity between conditions, three specific aims were established. First, the number of activated brain areas for ME and MI was compared. A Wilcoxon test was employed to evaluate differences in the number of activated areas reported for each condition, for this analysis we exclude studies that reported only ROI activation. Second, the frequency of activation by brain area was analyzed. A log-linear analysis was conducted to examine the relationship between (categorical variables)

brain area activation and condition (MI and ME), focusing on the interaction of activity by condition. Third, the brain areas predominantly active in each condition were compared. Absolute and relative frequencies were calculated for brain areas reported as more active during either ME or MI. Additionally, the frequencies of the brain areas reported as active during visual or kinesthetic motor imagery were analyzed.

Results

To summarize and analyze the scientific evidence on similarity of brain activity during MI and ME, a systematic review was performed. Out of 444 identified studies, 18 met the inclusion after screening titles, abstracts, and full-text papers (Figure 1).

Figure 1
Flowchart of Study Selection



Note. * Studies could be excluded for more than one reason.

Overview of Included Studies

The 18 included studies comprised 313 participants, both male and female (with one study exclusively on male subjects), all healthy adults with mean age of 32.97 (SD=13.01) years (ranging from 20 to 62). Sample sizes varied from 6 to 48 participants, with most studies (55.5%) including between 10 and 20 participants, two studies with fewer than 10, and 33% more than 20 participants. Geographically, 33% of the studies were conducted in North America, 28% in Europe, 22% in Asia, and 17% were cross-continental. All studies were published in English. The majority analyzed motor skills involving hand movements (e.g., finger sequence, chopstick movement, grasp and release, thumb abduction), with only one study analyzing a lower limb motor sequence. Brain activity was primarily assessed using fMRI (67%), followed by fNIRS (16%), EEG (5.5%), and PET (5.5%); one study employed both EEG and fMRI.

Overview for Brain Activity Results

A summary of the main results for brain activity in the included studies is presented in Table 1. Three studies focused on ROI brain areas (Matsuo et al., 2020; Porro et al., 2000; Wriessnegger et al., 2008), commonly assessing BA1 in three studies, BA4, BA6, and BA9 in two studies, and BA8 in one study. Half of the studies only assessed activity in the cerebral cortex, while the other half included additional brain regions (e.g. cerebellum, thalamus).

For the risk of bias assessment, most of the studies described fairly the sample of the participants including aspects of handedness, health status, age, and MI capacity. Due to the study's aim of comparing brain activity during MI and ME, none of the studies included treatment (or exposure). However, all of them include assessment methods for brain activity in both groups (see Table 2 for specific details per question).

Table 1

Summary for Principal Results for Brain Activity

Reference	Sample	Motor Skill	Instrument	Total areas reported	Principal results for brain activity
(Zapparoli et al., 2013)	Healthy young adults Mean age = 27 yrs. $n = 24$ Healthy older adults Mean age = 60 yrs. $n = 24$	Finger movements	fMRI	ME $n = 7$ MI $n = 7$	ME = MI: superior frontal gyrus, inferior temporal gyrus, SMA, cerebellum, premotor cortex (BA6), parietal cortex, pallidum, thalamus ME > MI: Primary motor cortex (BA4), SMA, cerebellum
(Wang et al., 2014)	Healthy young adults Mean age = 21 yrs. $n = 19$ Healthy older adults Mean age = 62 yrs. $n = 20$	Finger movements	fMRI	ME $n = 8$ MI $n = 2$	ME for both age groups: premotor cortex, supplementary motor cortex (SMA), primary motor cortex (M1), cerebellum, thalamus, parietal lobule, fusiform lobe, superior frontal lobe, putamen, and superior temporal lobe. MI for both groups: primary motor cortex (M1), supplementary motor cortex (SMA), premotor cortex
(Zich et al., 2015)	Healthy young adults Mean age = 23 yrs. $n = 22$	Sequential finger-tapping task	EEG and fMRI	ME $n = 3$ MI $n = 1$	ME: Primary motor area (BA4), supplementary motor area (BA6), sensorimotor cortex (BA1). KMI: sensorimotor cortex (BA1).
(Nair et al., 2003)	Adults Age range = 25-40 $n = 8$	Finger sequence	fMRI	ME $n = 6$ MI $n = 6$	MI versus ME: (unilateral and bilateral): sensorimotor cortex, SMA, superior and inferior parietal

Reference	Sample	Motor Skill	Instrument	Total areas reported	Principal results for brain activity
(Hanakawa et al., 2003)	Healthy adults Mean age = 32 n = 10	Finger tapping task	fMRI	ME n = 9 MI n = 9	lobule, cerebellum, precuneus. MI = ME: intraparietal sulcus (BA40, 7), supramarginal gyrus (BA40), superior and inferior precentral sulcus (BA6, 44), medial frontal cortex (BA6), posterior cerebellum, middle and inferior frontal gyrus (BA9, 46, 47), fusiform gyrus (BA18), putamen. ME > MI: precentral gyrus (BA4, 6), anterior cerebellum, parietal/temporal operculum (BA40, 42), medial frontal gyrus (BA6), superior parietal lobule (BA5), posterior central gyrus (BA1, 2, 3) MI > ME: dorsal and posterior superior parietal cortex (BA7), precentral sulcus, middle frontal gyrus (BA6).
(Porro et al., 2000)	Healthy Mean age = 22 n = 14	Sequential finger to thumb opposition movements	fMRI	ROI	ME and MI for four ROI: postcentral gyrus (S1), central gyrus (M1), premotor cortex, supplementary motor cortex. KMI > VMI: M1, premotor cortex, SMAME > KMI and VMI: M1
(Sharma Baron, 2014)	Older adults: Mean age = 56.4 n = 13 Young adults: Mean age = 27.4 n = 13	Finger thumb opposition sequence	fMRI	ME n = 3 MI n = 3	ME and MI: primary motor cortex (BA4), PMd, parietal lobe, cerebellum MI: activity in BA4p was greater in older adults, BA4a was lower. MI > ME: BA4p in both age groups ME > MI: BA4a in young group
(Guillot et al., 2009)	Healthy adults Mean age = 26 yrs. n = 13	Motor sequence of lower limbs Finger sequence task	fMRI	ME n = 14 MI n = 20	ME peaks: primary motor area (BA4), lateral dorsal premotor cortex (BA6), medial surfaces of the frontal cortex (SMA and pre-SMA regions), inferior frontal

Reference	Sample	Motor Skill	Instrument	Total areas reported	Principal results for brain activity
					areas (BA44), cingulate cortex (BA24), primary sensory areas (BA1, 2, 3), inferior parietal lobule (BA40), superior parietal region (BA5), anterior and posterior parts of the putamen, globus pallidus, caudate nucleus, and anterior and posterior cerebellar regionsVMI: primary (BA17) and associative visual areas (BA18, 19), inferior parietal lobule (BA40), right superior (BA7) and inferior (BA31) parietal areas, frontal lobe, primary motor area (BA4), lateral (BA6) and medial premotor areas (anterior and posterior parts of the SMA), dorsolateral (BA46) and rostral (BA10) prefrontal areas, putamen (anterior and posterior parts globus pallidus), and cerebellar hemispheres.KMI: medial and lateral premotor areas, prefrontal regions, inferior and superior parietal areas, basal ganglia and cerebellar cortex, primary motor cortex (BA4), lateral (BA6), and medial premotor areas (anterior and posterior parts of the SMA), inferior (BA44, 45) and dorsolateral prefrontal areas (BA9, 46), somatosensory areas (BA1, 2, 3), superior (BA5, 6, 7) and inferior (BA40) parietal lobules. ROIs: presupplementary motor area (pre-SMA), supplementary
(Matsuo et al., 2020)	Healthy adultsMean age = 29yrs. <i>n</i> = 21	Self-feeding task	NIRS	ROI	

Reference	Sample	Motor Skill	Instrument	Total areas reported	Principal results for brain activity
(Wriessnegger et al., 2008)	Healthy adults Mean age = 26.5 n = 16	Hand movement, tapping task	NIRS	ROI	motor area (SMA), prefrontal cortex (PFC), premotor cortex (PMA), and sensorimotor cortex (SMC). MI = ME: pre-SMA, PFC, SMC MI > ME: SMA and PMA ROI: prefrontal area, primary motor cortex (M1), somatosensory areas (S1). oxy-Hb: increases during ME and MI in all ROI (M1 and S1 increased more compared to prefrontal), compared to rest. MI process delayed oxygenation increase about 2s compared to ME. deoxy-Hb: stronger during ME compared to MI
(Neuper et al., 2005)	Healthy participants Mean age = 26.2 yrs. n = 14	Hand movement	EEG	ME n = 1 MI n = 2	ME: Sensorimotor (C3) VMI: Frontal and parieto-occipital (O1-O2) KMI: Sensorimotor (C3)
(Nakano, 2012)	Healthy adults Mean age = 24 yrs. n = 24	Hand movements (chopstick and hammer movements)	fNIRS	ME n = 10 MI n = 8	ME: Frontal (Pre-SMA, BA8), prefrontal cortex (BA9), frontal gyrus (BA45, BA44), subcentral area (BA43), premotor cortex (BA6), primary motor cortex (BA4), primary somatosensory cortex (BA1, BA2), inferior parietal lobule (BA40). MI: Frontal (BA8), prefrontal cortex (BA9), subcentral area (BA43), frontal gyrus (BA45, BA44), premotor cortex (BA6), primary somatosensory cortex (BA1, BA2).
(Lee et al., 2019)	Healthy participants Mean age = 30 yrs. n = 18	Grasp and release hand	fMRI	ME n = 9 MI n = 6	ME: primary motor area (BA4), premotor area, supplementary motor area (BA6), somatosensory area (BA1, BA3), supramarginal gyrus, thalamus, putamen,

Reference	Sample	Motor Skill	Instrument	Total areas reported	Principal results for brain activity
(Filimon et al., 2007)	Age range = 19-48n = 15	Reach (hand movement)	fMRI	ME n = 13MI n = 6	globus pallidus, cerebellum.VMI -1: premotor area (BA6), parietal lobule.VMI-3: premotor area (BA6), parietal lobule, supramarginal gyrus, and angular gyrus.KMI: supplementary motor area, premotor area (BA6), somatosensory area (BA2, BA3), parietal lobules, and supramarginal gyrus. ME: primary motor cortex, primary somatosensory cortex, dorsal premotor cortex, inferior frontal gyrus, supplementary motor area, cingulate cortex, posterior end of Sylvian fissure, superior and inferior parietal cortex, intraparietal sulcus (IPS), precuneus, cuneus, lingual gyrus, superior occipital gyrus, middle occipital gyrus, calcarine sulcus, and posterior end of the superior temporal sulcus.MI: superior parietal lobule, intraparietal sulcus, precuneus, dorsal premotor cortex, inferior parietal lobule, posterior end of the Sylvian fissure, supplementary motor cortex (SMA), inferior frontal gyrus (Broca's area).MI > ME: caudal intraparietal sulcus, angular gyrus, precuneus.ME > MI: primary motor cortex, primary somatosensory cortex, superior parietal lobule, medial IPS, supramarginal

Reference	Sample	Motor Skill	Instrument	Total areas reported	Principal results for brain activity
(Lacourse et al., 2005)	Healthy adults Mean age = 27yrs. $n = 12$	Hand motor sequence	fMRI	ME $n = 7$ MI $n = 7$	gyrus, middle occipital gyrus, dorsal premotor cortex, cuneus, lingual gyrus. ME > MI: frontal lobe clusters (SMA, M1, premotor areas). Postcentral and supramarginal gyri and superior temporal lobe, cerebellar and thalamus in novel participants MI > ME: caudate nucleus in novel ME > MI: SMA, cingulate gyrus, SPL, temporal lobe, Rolandic area, insula, supramarginal gyrus, cerebellar, thalamus in skilled MI > ME premotor areas, superior and inferior frontal areas, supramarginal gyrus, IPL, medial temporal lobe in skilled
(Oosterhof et al., 2012)	Healthy adults	Hand movement	fMRI	ME $n = 4$ MI $n = 4$	MI and ME: planum temporale, anterior parietal cortex, supplementary motor area, frontal cortex.
(Lotze et al., 1999)	Healthy adults $n = 10$	Hand movement	fMRI	ME $n = 4$ MI $n = 2$	ME: supplementary motor area (SMA), premotor cortex (PMC), primary motor cortex (M1), somatosensory cortex (S1), anterior lobe cerebellum MI: supplementary motor area (SMA), premotor cortex (PMC), primary motor cortex (M1). MI ME: primary motor cortex (M1), somatosensory cortex (S1).
(Stephan et al., 1995)	Male adults Mean age = 47 $n = 6$	Hand movement, joy-stick sequence	PET	ME $n = 8$ MI $n = 7$	ME: primary sensorimotor areas, lateral premotor areas, cingulate, inferior and superior parietal, operculum, precuneus, upper vermis of the

Reference	Sample	Motor Skill	Instrument	Total areas reported	Principal results for brain activity
					cerebellumMI: medial and lateral premotor areas, superior and inferior parietal areas, SMA, precentral gyrus, anterior cingulate, precuneus, insula.

Note. EEG: electroencephalogram, fMRI: functional magnetic resonance imaging, PET: positron emission tomography, NIRS: functional near-infrared spectroscopy, ME: motor execution, VMI: visual motor imagery, KMI: kinesthetic motor imagery, MI: motor imagery

Table 2

Risk of Bias Assessment Using The Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies, for Each Question

Reference	1	2	3	4	5	6	7	8	9	10	11	12	13	14
(Zapparoli et al., 2013)	Yes	Yes	CD	Yes	No	NA	NA	NA	Yes	NA	Yes	NA	NA	Yes
(Wang et al., 2014)	Yes	Yes	CD	Yes	No	NA	NA	NA	Yes	NA	Yes	NA	NA	Yes
(Zich et al., 2015)	Yes	Yes	CD	Yes	No	NA	NA	NA	Yes	NA	Yes	NA	NA	Yes
(Nair et al., 2003)	Yes	Yes	CD	Yes	No	NA	NA	NA	Yes	NA	Yes	NA	NA	Yes
(Hanakawa et al., 2003)	Yes	Yes	CD	CD	No	NA	NA	NA	Yes	NA	Yes	NA	NA	Yes
(Porro et al., 2000)	Yes	Yes	CD	CD	No	NA	NA	NA	Yes	NA	Yes	NA	NA	Yes
(Sharma Baron, 2014)	Yes	Yes	CD	Yes	No	NA	NA	NA	Yes	NA	Yes	NA	NA	Yes
(Guillot et al., 2009)	Yes	Yes	CD	Yes	No	NA	NA	NA	Yes	NA	Yes	NA	NA	Yes
(Matsuo et al., 2020)	Yes	Yes	CD	Yes	No	NA	NA	NA	Yes	NA	Yes	NA	NA	Yes
(Wriess-negger et al., 2008)	Yes	Yes	CD	Yes	No	NA	NA	NA	Yes	NA	Yes	NA	NA	Yes
(Neuper et al., 2005)	Yes	Yes	CD	Yes	No	NA	NA	NA	Yes	NA	Yes	NA	NA	Yes
(Nakano, 2012)	Yes	Yes	CD	Yes	No	NA	NA	NA	Yes	NA	Yes	NA	NA	Yes
(Lee et al., 2019)	Yes	Yes	CD	Yes	No	NA	NA	NA	Yes	NA	Yes	NA	NA	Yes
(Filimon et al., 2007)	Yes	Yes	CD	CD	No	NA	NA	NA	Yes	NA	Yes	NA	NA	Yes

Reference	1	2	3	4	5	6	7	8	9	10	11	12	13	14
(Lacour- se et al., 2005)	Yes	Yes	CD	Yes	No	NA	NA	NA	Yes	NA	Yes	NA	NA	Yes
(Ooster- hof et al., 2012)	Yes	Yes	CD	Yes	No	NA	NA	NA	Yes	NA	Yes	NA	NA	Yes
(Lotze et al., 1999)	Yes	NR	NR	NR	No	NA	NA	NA	Yes	NA	Yes	NA	NA	Yes
(Stephan et al., 1995)	Yes	Yes	CD	Yes	No	NA	NA	NA	Yes	NA	Yes	NA	NA	Yes

Note. CD: cannot determine; NR: not reported, NA: not applicable

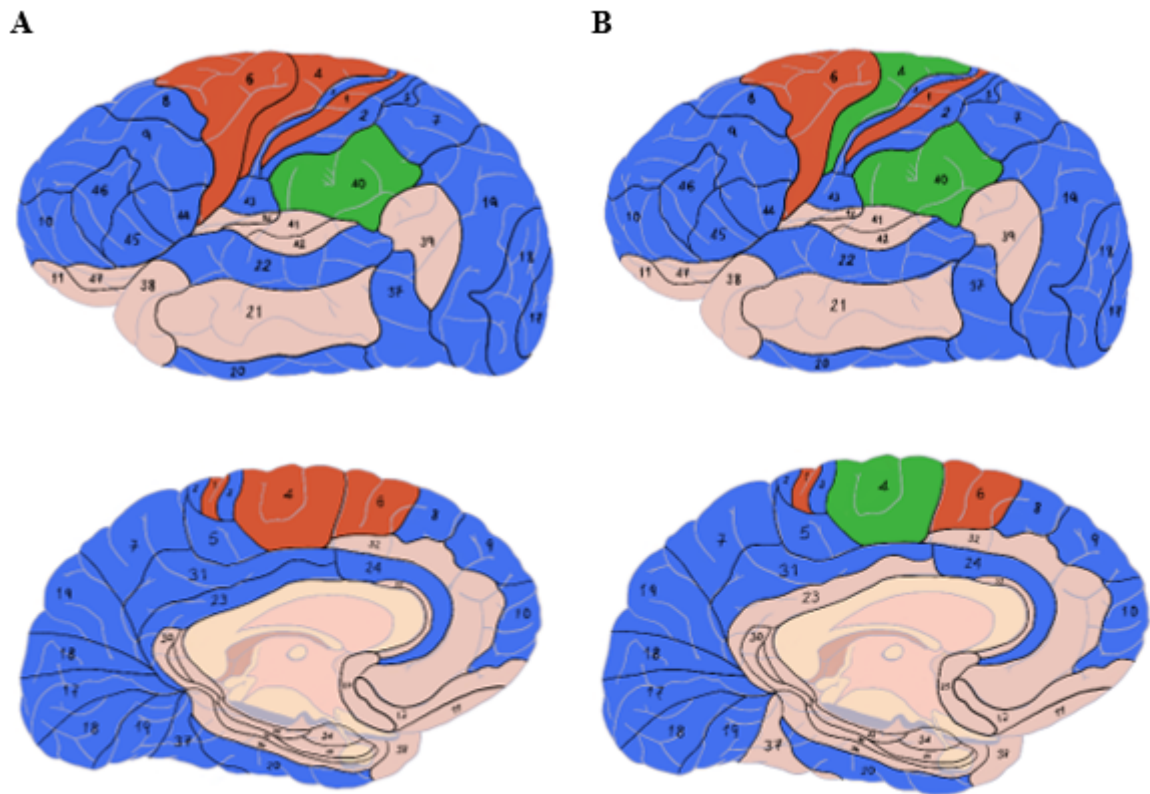
Out of the 18 studies, 12 reported the brain areas activated during both ME and MI, with eight also indicating whether the area was more active during ME or MI. For the first aim, we found a mean of 6.44 (± 3.65) brain areas reported as active during ME and 5.56 (± 4.31) during MI. Excluding the three studies that reported only ROI, the mean was 7.07 (± 3.69) active brain areas during ME and 6.00 (± 4.61) during MI. No significant difference was found between conditions ($W = 36.00$; $p = 0.122$; $n = 15$).

For the second aim, we coded the frequency each BA was reported as active for each condition across all included studies. Frequencies were categorized as follows: 1 to 5, from 6 to 11, and from 12 to 18. Figure 2 illustrates the areas with 12 to 18 frequencies reported in red, 6 to 11 in green, and 1 and 5 in blue. Six studies reported activation in the thalamus, putamen, globus pallidum and/or caudate nucleus for ME, while four studies reported activation in these areas for MI. Four brain areas (BA1, BA4, BA6, BA40) and the cerebellum were identified as having more frequent activation (reported in six or more studies). A log-linear analysis (to examine the relationship between variables) focusing on the interaction BA by condition showed no significant results ($\chi^2 = 0.52$, $gl = 4$, $p = .972$).

For the third aim, we coded the frequency with which each brain area was reported as more active during ME compared to MI (MEMI), more active during MI compared to ME (MEMI), or equally active in both conditions (ME=MI). Eight studies reported this comparison. Figure 3 shows the frequency for MEMI and MEMI for the most frequently reported BAs (BA1, BA4, BA6, and BA40) and the cerebellum. Additionally, one study reported the thalamus as more active during ME, while another reported the caudate nucleus as more active during MI.

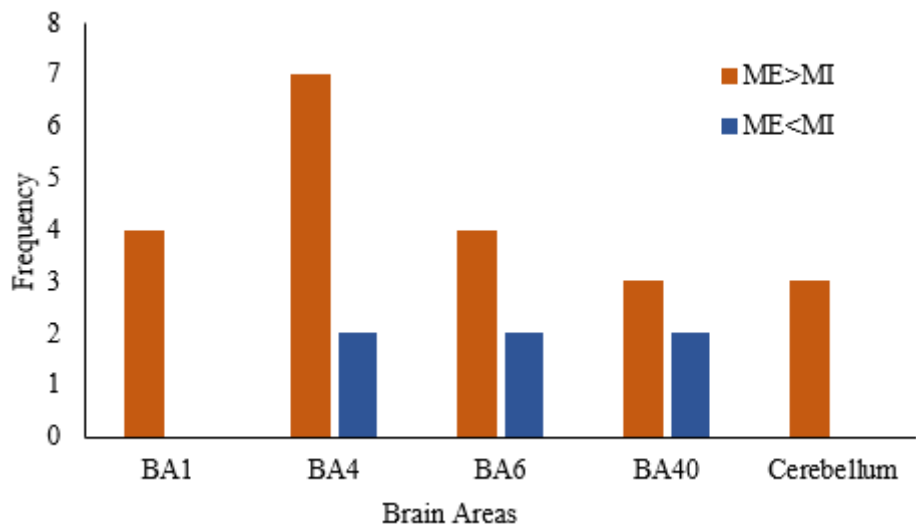
Four studies reported brain activity separately for visual and kinesthetic MI (Guillot et al., 2009; Lee et al., 2019; Neuper et al., 2005; Porro et al., 2000). For visual motor imagery (VMI), 13 BAs were reported as active in at least one study, compared to 11 for kinesthetic motor imagery (KMI). Figure 4 illustrates the reported frequency for VMI and KMI, highlighting areas with more frequent activation in red (more than three studies) and less frequent activation in blue (one or two studies).

Figure 2
Frequency Reported for Each BA During a) Motor Execution and During b) Motor Imagery (Lateral and Midsagittal Views)



Note. Frequency reported is represented as follows: 1 to 5 (blue); 6 to 11 (green); 12 to 18 (red). Nude indicates no frequency reported.

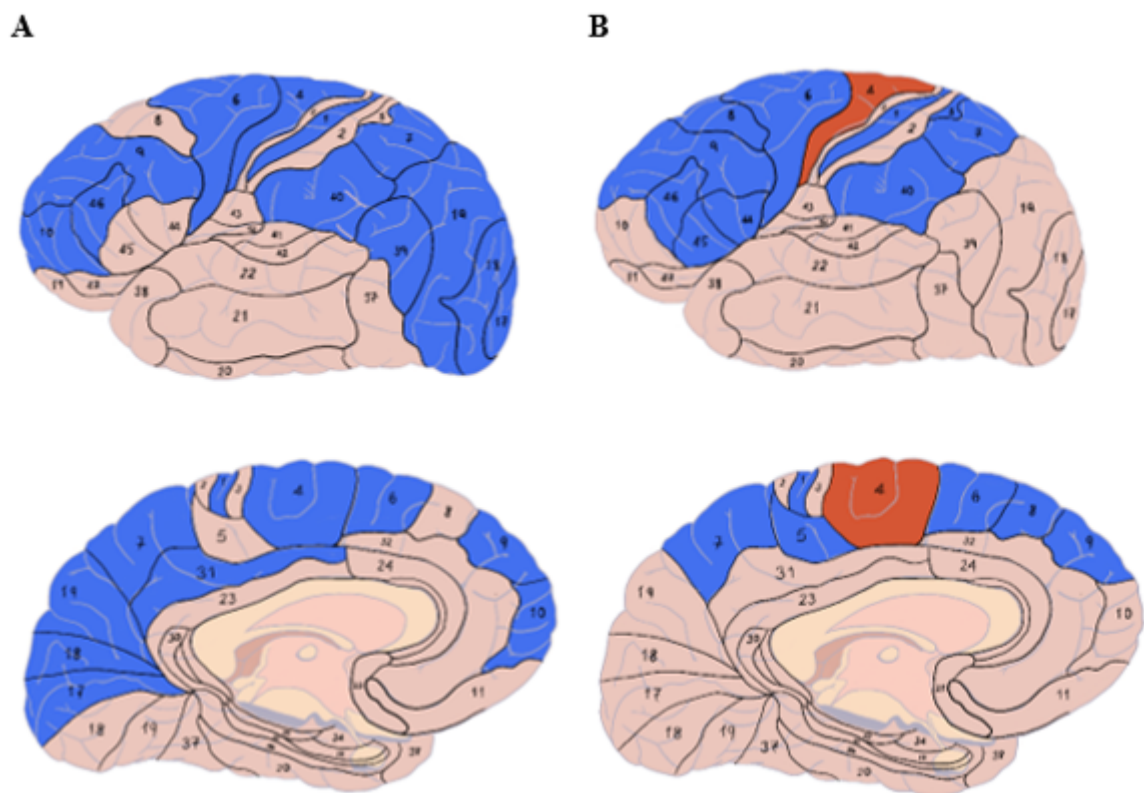
Figure 3
Frequency of Studies Reporting Higher Intensity on Each Brain Area (BA) for Each Condition, Either Motor Execution (ME) or Motor Imagery (MI)



Note. one study reported brain activity in two different samples (Sharma Baron, 2014).

Figure 4

Frequency Reported for Each BA During a) Visual Motor Imagery and During b) Kinesthetic Motor Imagery (Lateral and Midsagittal Views)



Note. Frequency reported is represented as follows: 1-2 (blue); 3-4 (green). Nude indicates no frequency reported.

Discussion

This study aimed to summarize and analyze the scientific evidence on the similarities of neural activity during motor imagery and motor execution. Three specific aims were established to assess this similarity. First, we compared the number of brain areas reported as active for each condition. Our data revealed that brain activity during ME and MI is similar in terms of the number of areas activated. Second, we compared the frequency of activation reported for each activated brain area across studies. We found that the five most commonly active areas were BA1, BA4, BA6, BA40, and the cerebellum, with no significant relationship in the frequency of activation between conditions. Finally, we examined the frequency with which each brain area was reported as more active during ME compared to MI, and vice versa. Our results align with previous reports indicating a mayor overlap in brain activity during ME and MI (Di Nota et al., 2016; Hardwick et al., 2018; Héту et al., 2013; Lee et al., 2019; Matsuo et al., 2020; Nakano, 2012; Wang et al., 2014; Zich et al., 2017).

Several studies have measured brain activity during ME and MI for various tasks (simple or complex), types of motor imagery (visual or kinesthetic), and participant characteristics (age and skill level), using different techniques (fMRI, EEG) (Matsuo et al., 2020; Nakano, 2012; Wang et al., 2014). Consistent with previous research (Hanakawa et al., 2003; Matsuo et al., 2020; Nakano, 2012; Wang et al., 2014), no mayor differences were identified in cerebral activation, with a large number of brain areas active during both ME and MI. BA1, BA6, BA4, and BA40 were reported frequently across studies. However, minor (non-significant) differences in brain activity were noted in a few areas (Di Nota et al., 2016; Hanakawa et al., 2003; Lee et al., 2019; Wang et al., 2014), consistent with our findings, that BA4 showed more intense activity during ME compared to MI.

Previous research has established that MI and ME rely on similar neural structures and processes (Jeannerod, 2001; Matsuo et al., 2020; Munzert et al., 2009). An activation likelihood estimation (ALE) meta-analysis (Héту et al., 2013) confirmed that MI consistently recruits premotor cortex areas (BA6) and parietal cortex (BA40, BA5, BA7), which are motor-related regions (Hanakawa, 2016; Hardwick et al., 2018; Héту et al., 2013; Jackson et al., 2003; Lee et al., 2019; Matsuo et al., 2020;

Nakano, 2012; Wang et al., 2014). Our results support that MI and ME rely on similar brain areas, including BA1, BA4, BA6 and BA40, frequently reported as active during both conditions. Additionally, similar to previous research, we found activity in the thalamus, putamen, and globus pallidum during ME and MI (Guillot et al., 2009; Hanakawa et al., 2003; Lacourse et al., 2005).

BA1 and BA40 function as sensory hubs in the perception of space and limb location during ME. BA6 is involved in planning for ME, while BA4 is responsible for both planning and execution (Héту et al., 2013). Previous research has noted that cerebral activity during MI differs somewhat from ME, particularly due to the inconsistent of the results focusing on the activity in BA4, which has generated some controversy (Hanakawa et al., 2003; Munzert et al., 2009; Neuper et al., 2005). These minor differences may be due to MI's role in planning during ME (Matsuo et al., 2020), with BA4 more related to movements (Hanakawa et al., 2003). In this study, BA1, BA6, and BA40 showed similar activity and intensity for both ME and MI, while BA4 showed similar frequency but differed in intensity.

The higher intensity of BA4 during ME compared to MI can be attributed to BA4's primary function in planning and execution (Héту et al., 2013), supporting the partially independent mechanisms suggested by Macuga and Frey (2012). The distinction between ME and MI lies in the actual execution of the movement, with BA4 not playing a primary role in MI (Hanakawa et al., 2003).

Imagination (e.g. motor imagery) shares some brain processes with real perception and action, but different imagery methods can lead to disparate activation patterns (Guillot et al., 2009; Neuper et al., 2005). Kinesthetic motor imagery promotes movement and sensation experiences, while visual motor imagery primarily promotes pictorial experiences (Lee et al., 2019; Neuper et al., 2005). These differences may result in different brain regions being activated. Neuper et al. (2005) found that for KMI activity was closer to the sensorimotor area, while VMI did not show a clear spatial pattern. Lee et al. (2019) observed different brain activity patterns between KMI and VMI, including supplementary motor area and insula regions. Guillot et al. (2009) reported that VMI activated more occipital and superior parietal regions, while KMI activated more motor-associated and inferior parietal regions. Consistent with these studies, we found differences between KMI and VMI in BA4, more frequently reported for KMI and in the occipital regions, more frequently reported for VMI.

These differences may be influenced by factors such as the type of motor task (simple or complex), type of MI (KMI or VMI), first- or third-person visualization perspectives, participant expertise (novel or expert), and age (Guillot et al., 2009; Hanakawa et al., 2003; Lee et al., 2019; Matsuo et al., 2020). However, due to insufficient information, we could not address these comparisons.

These results confirm that ME and MI rely on similar neural mechanisms, which may explain the effectiveness of mental practice as a complement to physical practice. Consequently, MI can be utilized in rehabilitation scenarios and sports performance. The objective analysis used to compare the three aims established to assess similarities is a strength of this study. Additionally, we included all available technologies (fMRI, fNIRS, EEG, and PET) to assess brain activity. Few limitations were noted, such as the lack of information from included studies, which precluded analysis of cerebral activation by motor task type, MI types (visual or kinesthetic), and participant characteristics (age and expertise).

In conclusion, based on our results, similarities on brain activity during ME and MI are evident in the number of areas activated and the frequency of brain activity in at least four areas (BA1, BA4, BA6, BA40) and the cerebellum. Most brain areas related to movement showed imagery-related activity, supporting the idea that MI and ME share major neural mechanisms.

Ethics Committee Statement

Not applicable, as this study is a literature review.

Conflict of Interest

The authors declare no conflicts of interest.

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Author's Contributions

Author contributions were defined according to the CRediT taxonomy: Conceptualization: Jiménez-Díaz, Morales-Scholz, Araya-Vargas; Methodology: Jiménez-Díaz, Morales-Scholz, Araya-Vargas; Software: Jiménez-Díaz Araya-Vargas; Validation: Jiménez-Díaz, Morales-Scholz, Araya-Vargas; Formal Analysis: Jiménez-Díaz Araya-Vargas; Investigation: Jiménez-Díaz, Morales-Scholz, Araya-Vargas; Resources: Jiménez-Díaz Araya-Vargas; Data Curation: Jiménez-Díaz Araya-Vargas; Writing – Original Draft Preparation: Jiménez-Díaz; Writing – Review Editing: Morales-Scholz Araya-Vargas; Visualization: Jiménez-Díaz, Morales-Scholz, Araya-Vargas; Supervision: Jiménez-Díaz; Project Administration: Jiménez-Díaz; Funding Acquisition: No funding. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request at .

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