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## NEUROSCIENCE FOREFRONT REVIEW

# NEURAL PLASTICITY DURING MOTOR LEARNING WITH MOTOR IMAGERY PRACTICE: REVIEW AND PERSPECTIVES

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**Abstract—In the last decade, many studies confirmed the benefits of mental practice with motor imagery. In this review we first aimed to compile data issued from fundamental and clinical investigations and to provide the key-components for the optimization of motor imagery strategy. We focused on transcranial magnetic stimulation studies, supported by brain imaging research, that sustain the current hypothesis of a functional link between cortical reorganization and behavioral improvement. As perspectives, we suggest a model of neural adaptation following mental practice, in which synapse conductivity and inhibitory mechanisms at the spinal level may also play an important role. © 2016 Published by Elsevier Ltd on behalf of IBRO.**

**Keywords: Motor imagery, TMS, Learning, Plasticity.**

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## INTRODUCTION

Motor skills, such as playing piano, basketball, or writing, are developed through extensive practice over several years. Movement learning involves several interconnected components: processing and collecting sensory inputs relevant to action, applying a series of decision-making strategies that define movement parameters (e.g., direction, duration, force), and activating feed-forward, reactive, and biomechanical control processes during motor performance (Wolpert and Flanagan, 2001). Two experimental paradigms are frequently used to study the neural processes underlying motor skill learning (Doyon and Benali, 2005; Shadmehr et al., 2010 for a review): (1) motor sequence learning with the incremental acquisition of movements in a specific behavior and (2) adaptation learning with the compensation for changes in the body or environmental dynamics. In both paradigms, several phases can be distinguished: (i) a fast phase, in which performance improvement occurs within the first training session; (ii) a consolidation phase, in which an enhancement of performance occurs at least 6 h after the first practice session; (iii) a slow phase, in which further gains can be achieved across several training sessions; (iv) an automatic stage, in which the motor task is performed automatically with poor cognitive demand; and (v) a retention state, in which the motor performance can be executed in the absence of any practice after a long delay (Doyon and Benali, 2005; Halsband and Lange, 2006).

Physical practice is undeniably vital for the acquisition and the consolidation of new motor skills (Robertson et al., 2004). Two well-assessed complementary methods for motor skill learning are action observation (Mattar and Gribble, 2005; Naish et al., 2014 for a review) and motor imagery – MI (Pascual-Leone et al., 1995; Gentili et al., 2010; Gentili and Papaxanthis, 2015; Schuster et al., 2011). During action observation, visual information implicitly activates the so-called *mirror neuron* system (e.g., Iacoboni et al., 1999; Buccino et al., 2001) and may improve the observer's motor planning process (Pozzo et al., 2006; Sciutti et al., 2012). On the other hand, MI is the explicit or implicit mental representation of action without concomitant movements. Implicit MI is commonly involved in mental rotation tasks, while explicit MI is used when ones is *specifically* instructed to mentally simulate an action. Different modalities frame MI: kines-

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thetic (based on sensory information normally generated during actual movement), haptic (using cutaneous information to recreate the interaction with external objects), visual (with external and internal perspectives), or auditory. One can use these modalities independently or combine them to potentiate the activation of the sensorimotor system during MI. Mental practice by means of MI is increasingly used for motor learning in healthy people (Dickstein and Deutsch, 2007) or for motor rehabilitation in patients (Malouin et al., 2013a).

Over the past twenty years, many studies have provided relevant information about the neurophysiological mechanisms underlying MI. Nonetheless, the neural stages (cortical, subcortical and spinal) involved in MI process are mainly probed separately. It is not clear yet whether motor learning with MI equally affects central and peripheral neural structures. This review aims to present recent findings on the neural aspects following MI practice, to provide guidelines about the strategy for motor learning with MI, and to suggest a model of neural adaptation as a perspective for future research. We particularly discussed data from transcranial magnetic stimulation (TMS) studies, supported by those recorded during brain imaging research. TMS is a reliable and non-invasive tool used in fundamental and clinical research to probe the level of corticospinal excitability during MI and the cortical plasticity after MI practice.

## WHAT DO BEHAVIORAL AND COGNITIVE NEUROSCIENCES REVEAL ABOUT MI?

For many years now, scientists have tried to understand the functional and neural similarities between mental and actual movements. The mental chronometry paradigm, aiming to correlate the temporal content of actual and mental actions, has been extensively used. The results showed that the duration of both movements is conventionally equivalent (see Guillot and Collet, 2005 for a review). Regarding the neurophysiological component, previous reviews, mainly focusing on fMRI data, have excellently presented the neural link between mental and actual states (Hétu et al., 2013). However, single-neuron recording studies showed specific activations during MI in comparison to actual movement (Amador and Fried, 2004; Leuthardt et al., 2004; Anderson et al., 2011). For example, Amador and Fried (2004) showed that the neurons in the supplementary motor area differentiated between actual and imagined movements.

To extent these results, we presented TMS studies that assessed the neural processes of MI and the mechanisms of neural modulation following mental practice with MI. This non-invasive technique with high temporal resolution presents many advantages to assess the level of corticospinal and intracortical excitability. TMS is extensively used in cognitive neuroscience to determine the involvement of brain areas and the temporal specificity. In the mid-80s, Barker et al. (1985) presented a technology designed to stimulate cortical areas that was less painful than electrical stimulation. The authors used a magnetic field to activate neurons located a few centimeters under the coil. A brief stimulation over the cortical representation of a body part in M1 activates the corticospinal track and induces a response in the corresponding contralateral muscle. This response is called a motor-evoked potential (MEP, see Loporto et al., 2011 for physiological and technical details). TMS can also be placed over other cortical areas to disrupt the activation of the targeted area and to explore the neural network underlying a specific behavior. Nowadays, this non-invasive technique is extensively used in fundamental and clinical studies and, by extension, in MI paradigms. A total of 164 articles, published between 1995 and 2016, were found through an online search with the PubMed (https://www.ncbi.nlm.nih.gov/pubmed/) and Google Scholar (https://scholar.google.fr/) databases, combining the terms "TMS" with "mental imagery", "motor imagery" or "mental practice". We selected all articles that presented mental/motor imagery and mental practice studies that used TMS as a technique to probe the underlying neurophysiological mechanisms (see Table A.1 in Appendix). Eighty-three TMS papers on this topic, i.e. 50%, have been published since 2010, showing the significant growing interest for this research field. When placed over M1, TMS elicited MEPs in the contralateral effector, a probe of corticospinal excitability, mostly during explicit mental imagery (78% of the papers; see Fig. 1) and very few during implicit mental imagery (2.4%). To our knowledge, only five studies (3%) measured corticospinal excitability before and after mental practice with MI, controlling cortical plasticity (Pascual-Leone et al., 1995; Bassolino et al., 2013; Leung et al., 2013; Avanzino et al., 2015; Volz et al., 2015). Finally, TMS placed over non-M1 areas in mental imagery studies were used to disrupt activity in this area and to assess its relevance to the mental task or to further understand the neural network (e.g., Ganis et al., 2000; Lebon et al., 2012b).

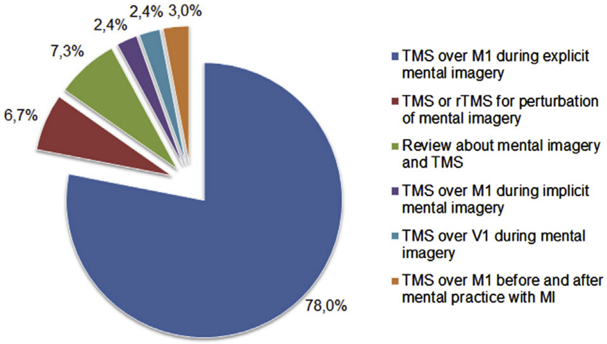

**Fig. 1.** Graphic distribution of transcranial magnetic stimulation (TMS) studies in mental imagery research. Mental imagery embraces motor imagery that includes all sensorimotor information that one can experience when interacting with the environment and non-motor imagery that involves any other activities that do not affect one's motor behavior (e.g., mental picturing or mental rotation of letters). Explicit and implicit mental imagery is the mental representation that one experiences consciously and unconsciously, respectively. Mental practice is the repetition of mental representations used for learning, training and rehabilitation. M1 = primary motor cortex; V1 = primary visual cortex; rTMS = repetitive TMS.

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