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NSR-3893; No. of Pages 8

ARTICLE IN PRESS

Neuroscience Research xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Neuroscience Research

journal homepage: www.elsevier.com/locate/neures

Review article

Organizing motor imageries

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ARTICLE INFO

Article history:
Received 29 August 2015
Received in revised form 6 November 2015
Accepted 9 November 2015
Available online xxx

Keywords:
Imagination
Movement
Simulation
Embodiment
Brain machine interface
Neurorehabilitation

ABSTRACT

Over the last few decades, motor imagery has attracted the attention of researchers as a prototypical example of 'embodied cognition' and also as a basis for neuro-rehabilitation and brain–machine interfaces. The current definition of motor imagery is widely accepted, but it is important to note that various abilities rather than a single cognitive entity are dealt with under a single term. Here, motor imagery has been characterized based on four factors: (1) motor control, (2) explicitness, (3) sensory modalities, and (4) agency. Sorting out these factors characterizing motor imagery may explain some discrepancies and variability in the findings from previous studies and will help to optimize a study design in accordance with the purpose of each study in the future.

Contents

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http://dx.doi.org/10.1016/j.neures.2015.11.003
0168-0102/

1. What is motor imagery?

Motor imagery, or motor imagination, has been a popular topic of research in, but not limited to, psychology, cognitive neuroscience, neurophysiology, neuroimaging and clinical neurology. One reason for such disseminated interest stems from a unique property of motor imagery as a cognitive ability strongly grounded to the body, or 'embodied' cognition. An archetypal example is motor imagery used implicitly for visual shape discrimination (Parsons et al., 1995). Moreover, motor imagery, albeit a cognitive entity, appears to share the control mechanisms and neural substrates with actual movement, providing a unique opportunity to study neural control of movement. Strong supporting evidence for this statement is available from many transcranial magnetic stimulation (TMS) studies showing motor imagery enhanced corticospinal excitability (Izumi et al., 1995; Kasai et al., 1997; Liang et al., 2007; Mizuguchi et al., 2013; Stinear and Byblow, 2003). Motor imagery also draws attention as a technique for sports training and neuro-rehabilitation. More recently, motor imagery offers an essential basis for the development of brain–machine/brain–computer interfaces (BMIs/BCIs) for physically disabled persons.

Motor imagery is a cognitive ability commonly defined as 'mental simulation' or 'mental rehearsal' of movements without actual movements (Decety, 1996; Grush, 2004; Jeannerod, 1994). This definition has been widely accepted in the field, and reasonably encompasses a variety of motor imagery studies conducted so far. However, it should be noted that motor imagery, as it currently stands, does not necessarily represent a homogenous capability. From the perspective of motor control, motor imagery relates to motor planning and motor preparation, which are possibly related to 'suppressed' motor execution. Neural mechanisms should be different, depending on which stage of motor control is mainly involved in a particular motor imagery task or in an individual's strategy. Similarly, motor imagery can be divergent, depending upon the extent to which a task or a strategy is associated with virtual perception of visual, auditory, somatosensory (kinesthetic), and vestibular sensations, all of which can be associated with overt actions. In addition, there seems to be a gradient as to what extent imagery is intentionally generated and becomes conscious; namely, a graded distinction may be possible between conscious/explicit motor imagery and unconscious/implicit motor imagery. These factors are not always described or discussed in motor imagery studies, but they can substantially influence neuropsychological, physiology and imaging results.

2. Factors characterizing motor imagery

To aid the interpretation of previous motor imagery studies and also guide future studies, I propose to organize "motor imageries" based on four factors: (1) motor control, (2) explicitness, (3) sensory modality, and (4) agency (Table 1).

2.1. Motor control

An ability of motor imagery is conceivably built upon the mechanisms of neural control for movement. In motor imagery studies as well as actual movement studies, it is essential to report the involved effector(s) and movement patterns/parameters to be imagined (e.g. single or repetitive, regular or irregular, frequency, amplitude, force level and so forth). The effector that should be involved in motor imagery is relatively straightforward, and the effects of imagined effector onto distribution of brain activity have been well characterized (discussed in 4.2). Also, some previous studies examined influence of force levels during motor imagery onto brain activity (Bonnard et al., 2007; Mizuguchi et al., 2014) and corticospinal excitability (Bonnard et al., 2007; Mizuguchi et al., 2013). In contrast, it has not been well recognized that a few different stages of motor control can be involved in motor imagery. Those stages include planning, preparation and execution. A series of neurophysiological studies by Hoshi and colleagues prompted the author to bear this idea in mind. In the planning stage of delayed instruction motor tasks, only partial information is given to an organism to compute a motor command, while in the preparation stage, the motor command is already completed and the organism only waits for a GO cue (Nakayama et al., 2008). At the planning stage, for example, a target is instructed but which arm to use is not informed yet. Hence, a few possible action plans can exist at the planning stage while a motor command can be uniquely mapped onto muscles at the preparation stage. Motor imagery should have counterparts of these stages, if motor imagery is defined as simulation of motor control processes. However, the extent to which each stage is involved in a particular motor imagery task would differ depending on task designs and instructions.

The planning or preparation stage of motor control does not accompany muscle activity, whereas the execution stage does. Because motor imagery should not accompany overt muscle contractions, the process of motor inhibition or suppression needs to be implemented (Guillot et al., 2012). In this regard, motor imagery may not be clearly defined in amputees or paralyzed individuals because of the difficulty in drawing a line between imagery

Table 1
Factors of motor imagery.

Factors	Selected references
F1 (motor control)	
F1.1: Stages (planning, preparation, execution[a])	Hanakawa et al. (2008) and Raffin et al. (2012)
F1.2: Effectors	Ehrsson et al. (2003), Hanakawa et al. (2005) and Hanakawa et al. (2007)
F1.3: Patterns and parameters (e.g. force level, complexity)	Bonnard et al. (2007), Mizuguchi et al. (2013, 2014) and Hanakawa et al. (2003)
F2 (explicitness)	
F2: Explicit/intentional or implicit/evoked	Hanakawa et al. (2008) and Osuagwu and Vuckovic (2014)
F3 (sensory modality)[b]	
F3.1: Visual	Guillot et al. (2009), Stinear et al. (2006) and Iseki et al. (2008)
F3.2: Somatosensory (kinesthesia)	Naito et al. (2002, 2011), Guillot et al. (2009) and Stinear et al. (2006)
F3.3: Auditory	Bidet-Caulet et al. (2005) and Harris and de Jong (2014)
F3.4: Combined/vestibular[c]	Blanke et al. (2005) and Ionta et al. (2011)
F4 (agency)	
F4: First-person or third-person perspective	Ruby and Decety (2001)

[a] Motor execution should not be defined as motor imagery by definition, but motor imagery studies may include such conditions as partially suppressed or aberrant execution.
[b] References include studies on sensory triggered and non-triggered imagery.
[c] Illusory vestibular sensation induced by combined visual and somatosensory stimuli.