Review article
Organizing motor imageries
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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.

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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, physiolog- ogy 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 effectors 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...
Fig. 1. A flow chart to sort out motor imagery factors (Table 1). The factors are limited to the planning, preparation and execution stages of motor control (F1.1) and the explicitness (F2) of Table 1 for simplicity. Sensory-guided motor control often starts from an abstract motor plan (planning) followed by formation of an immediately executable program mapped onto muscles (preparation), resulting eventually in physical movements that accompany muscle activity (execution). This concept can be employed for organizing motor imageries. Imagine, for example, that you are a rugby football player who is about to receive a ball from a passer. At this planning stage, you have a few options for the next move (kicking, passing, and running). After you have gathered necessary information (e.g. other players’ positions) to allow you to select one of the options, you may imagine the particular movement by invoking a specific motor program without muscle contraction (preparation). You can also perform the movement with some muscle activity (partially suppressed execution). In both planning and preparation stages, you may voluntarily imagine these behaviors without receiving any external stimuli (called explicit imagery in this article). Alternatively, a visual scene of another player playing rugby may unintentionally evoke your motor program. This phenomenon is called implicit imagery here. Among these, explicit motor imagery at a preparation stage is the most typical motor imagery.

(execution with full suppression of muscle activity) and execution to their best. There is another point of consideration in amputees. Although amputees are reported to activate the motor cortex robustly during “motor imagery” (Erland, et al., 1996), they may activate muscles in their stump when asked to try moving their phantom limb. Such aberrant motor execution can be distinguished from motor imagery, by monitoring muscle activity from stumps (Raffin, et al., 2012). In this study, when stump muscle activity was suppressed, motor cortical activity disappeared. These facts highlight the importance of instructions for the suppression of muscle activity in any part of the body during motor imagery. Another lesson is important for ensuring absence of any overt muscle activity correlated with motor imagery tasks. Visual inspection only cannot rule out isometric muscle contraction or slight muscle tensioning, and thus electromyography (EMG) monitoring of activity is recommended whenever possible to distinguish motor imagery from partially suppressed motor execution or aberrant motor execution. Without muscle activity, motor imagery should primarily involve the planning and/or preparation stages of motor control.

In the previous motor imagery studies, little attention has been paid to the factors of the motor control stage in a given motor imagery task. A motor imagery task should correspond to either motor planning (a few motor repertoire possible at this stage) or motor preparation (movement uniquely specified at this stage). Another poorly considered factor thus far is the explicitness of motor imagery as explained in the next section. I summarize how to sort out these factors in Fig. 1 to foster future discussions.

2.2. Explicitness

Can motor imagery be unintentionally generated? Are we always conscious about the generation of motor imagery? These are difficult questions to answer because the evidence is scarce; at the same time, these are important questions considering the emergence of neuroscience of consciousness. Intentionally generated motor imagery is a typical type of motor imagery, which is also called explicit motor imagery, while unintentionally generated motor imagery is called implicit motor imagery. Implicit motor imagery has mostly been studied as a sensory-triggered motor-related process (e.g. observation of movement), but its relationship with explicitly instructed motor imagery has not been well characterized until recently. Hanakawa and colleagues (2008) examined brain activities evoked by motor imagery and motor execution of finger tapping along with those evoked by instruction cues (numbers). Participants planned a movement in response to an instruction cue, and after a variable delay period, they performed either motor imagery or motor execution in response to another type of cue. At the presentation of an instruction cue, subjects should recollect a motor representation in an abstract form at the planning stage of motor control applicable to both movement and imagery. However, at this stage, subjects were not asked to do anything explicitly; hence, this instruction-cue-related mental process seems to correspond to ‘implicit motor imagery’. This study primarily looked at a first-person perspective, kinesthetic imagery at a planning/preparation stage of motor control explicitly instructed by visual cues. A substantial overlap was found between the instruction cue-induced brain activity and the explicit motor imagery-related brain activity in the premotor-parietal cortices, suggesting a shared neural mechanism between implicit motor imagery and explicit motor imagery at a planning stage of motor control. A similar finding has been reported for the comparison of implicit imagery during mental rotation of hands and explicit imagery of hands, using a frequency analysis of electroencephalography (EEG) signals (Osuagwu and Vuckovic, 2014).

2.3. Sensory modality

Conventionally, virtual sensory experiences during motor imagery are classified into two: a kinesthetic type and a visual type. Indeed, there are a few more types of sensory experiences that can be coupled with motor imagery in a virtual form. This idea has been inferred from studies on perception of sensory stimuli tightly coupled with movement. Such stimuli often induce automatic activation of motor representations, and exploration behind
these phenomena is an important topic surrounding motor imagery research. A famous example is observations of movements. Discovery of mirror neurons and mirror neuron systems, which are activated during both movement and movement observations, clearly indicates that analysis of visual information of a movement overlaps with that of execution of the same movement (Rizzolatti and Sinigaglia, 2010). Recent evidence suggests that the mirror neuron systems may play a role in motor imagery through suppression of movement (Kraskov et al., 2009; Vigneswaran et al., 2013). Other examples include the perception of biological motion (Saygin et al., 2004), conditional cues that indirectly specify movement (Hanakawa et al., 2008), auditory stimuli such as sound of footsteps (Bidet-Caulet et al., 2005) or music (Harris and de Jong, 2014), deep sensory stimuli inducing motor illusion (Naito et al., 2002b, 2011), and the combination of somatosensory and visual stimuli, which can evoke vestibular sensations (Ionta et al., 2011). It is taken for granted that motor imagery recruits the recollection of sensory experiences tightly coupled with movements. Differences in imagery strategy substantially modulate a pattern of brain activity and corticomotor excitability during motor imagery tasks (Guillot et al., 2009; Stinear et al., 2006). Thus, motor imagery researchers should consider all of the sensory types that can be associated with movement and do their best to characterize which sensory type is a primary target of the research.

2.4. Agency

Motor imagery has been classified into a first-person perspective (imagining themselves performing a given action) and a third-person perspective (imagining a third party performing the same action), a matter of perspective taking or agency. This distinction has been used in visual-type motor imagery (Ruby and Decety, 2001), yet the concept can be theoretically extended to other modalities (e.g. auditory). Moreover, although traditional motor imagery researches tend to focus on the first-person perspective, studies on third-person perspective motor imagery can naturally extend into the context of social neuroscience.

3. Neural correlates of motor imagery: implications from non-human primate studies

Some studies on non-human primates provide important insights into the neural mechanisms of motor imagery, although it is not possible to obtain introspections about animals’ strategy. Cisek and Kalaska (2004) trained monkeys with an instructed-delay reaching task in which a juice reward was delivered when monkeys reached the correct target after a GO signal (Cisek and Kalaska, 2004). After the monkeys had learnt the task, they implemented a new experiment in which the monkeys just observed a computer display that showed an unseen agent (an experimenter) performing the same task. The monkeys received a reward in the correct trials. Behaviorally, a saccade just before the reaching and licking movement before the reward delivery indicated that the monkeys anticipated the reaching target and the success of the task, respectively, performed by another agent. In not only the reaching but also the observation task, neurons in the dorsal premotor cortex represented the correct location of the target (a property of “directional tuning”) during the instructed delay period. Moreover, after GO signals, the dorsal premotor neurons reflected performance of reaching such as reaction times and errors. These were taken as evidence that the dorsal premotor cortex plays a role in the mental rehearsal of reaching movements in non-human primates. According to the proposed analysis of the motor imagery factors (Table 1), the observation condition of this experiment primarily investigated a preparation stage of reaching movement involving an upper limb implicitly induced by conditional visual cues from a third-person perspective. Activities at a motor planning stage, interpreted as mental rehearsal, have been recorded in the posterior parietal cortex such as the parietal reach region (PRR) (Cui and Andersen, 2011).

4. Neural correlates of motor imagery: human studies

In the 1990s, researchers started to explore the neural correlates of motor imagery, using positron emission computed tomography (PET), functional magnetic resonance imaging (fMRI), and magnetoencephalography (MEG). Those neuroimaging studies have converged to demonstrate that motor imagery tasks activate many cortical and subcortical regions that substantially overlap with those for movement execution (Ehrsson et al., 2003; Gerardin et al., 2000; Hanakawa et al., 2003, 2005, 2008; Iseki et al., 2008; Naito et al., 2002a; Parsons et al., 1995; Porro et al., 1996). The sharing of neural substrates between cognitive ability and movement execution initially deemed surprising, and motivated many researchers to jump into motor imagery research from various fields. It is established that motor imagery recruits cortical and subcortical regions relevant to movement execution. Still, some controversies exist in the literature, and the concept of motor imagery factors may in part provide an account for the discrepancy.

4.1. Primary motor cortex

A well-known controversy involves the magnitude and exact location of imagery-related activity within the primary motor cortex (M1). Using imagery of finger movement, some found significant activity in M1 (Lotze et al., 1999; Porro et al., 1996; Roth et al., 1996), but others did not (Dechent et al., 2004; Gerardin et al., 2000; Hanakawa et al., 2003, 2005, 2008; Naito et al., 2002a). First, the stage of motor control involved in a particular imagery task should influence the degree of M1 activity. The preparation stage of motor control likely induces M1 activity more robustly than the planning stage. Second, sensory modalities accompanied with motor imagery modulate a pattern of brain activity. When brain activity during motor imagery was compared between a kinesthetic type and a visual type, the visual type activated predominantly the visual-related areas and superior parietal lobule, whereas the kinesthetic type activated motor-associated structures and the inferior parietal lobule (Guillot et al., 2009). The kinesthetic imagery, but not visual imagery, modulates corticomotor excitability during motor imagery tasks (Stinear et al., 2006). Third, the visual experience of motor imagery can further be classified into a first-person perspective and a third-person perspective. Differences in perspective taking modulate a pattern of activity during motor imagery tasks, and the first-person perspective involved sensorimotor areas more markedly than the third-person perspective (Ruby and Decety, 2001). Finally, the discrepancy can also be explained by technical factors because there seem to be substantial differences in the definition of M1 across the studies. Previously, many researchers followed the nomenclature of the Talairach and Tournoux’s atlas, which is no longer used because of its obvious limitations. Some others used the posterior half of the precentral gyrus as a region of interest, but this region would encompass both pre-motor cortex and M1. Some others defined the “precentral knob” (Yousry et al., 1997), which was the established landmark representing hand movement, but this may only be one of the M1 subdivisions controlling hand movement. In fact, Ehrsson et al. (2003) identified activity in the anterior sector of M1 (M1a or old M1), but not in the posterior sector of M1 (M1p or new M1) during motor imagery of hands and feet while motor imagery of the tongue activated both M1a and M1p. This finding is in part
supported by another motor imagery study (Hanakawa et al., 2005). At this point, the best practice would be to use a probabilistic map for anatomical nomenclature. Another technical point is that if the studies did not confirm lack of muscle activity through EMG, then it might be difficult to rule out the effects of muscle contraction during imagery tasks (i.e. partially suppressed or aberrant motor execution).

4.2. Premotor and supplementary motor areas

Body-grounded aspects of motor imagery are underpinned by somatotopic organization of activities induced by motor imagery involving different body parts (Ehrsson et al., 2003; Hanakawa et al., 2005). Also, Hanakawa and colleagues (2007) provided a preliminary report that mental rotation of feet involved more dorsal motor and somatosensory areas than those involved in mental rotation of hands, in consistent with the motor and somatosensory "homunculus" (Fig. 2). These activities are paralleled with somatotopic organization of activity during action observation and execution mainly in the premotor and parietal areas (Buccino et al., 2001). Motor imagery of gait activates dorsal regions of motor-related cortices representing gait (Iseki et al., 2008; Malouin et al., 2003). These somatotopically organized motor imagery-induced activity includes premotor and supplementary motor areas, which are the most consistently revealed regions as the substrates of motor imagery (Ehrsson et al., 2003; Gerardin et al., 2000; Hanakawa et al., 2003, 2005, 2008; Iseki et al., 2008; Naito et al., 2002a; Parsons et al., 1995). These findings are reasonable considering that premotor and supplementary motor areas are the key structures at the planning and preparation stages of motor control (Hoshi and Tanji, 2004; Nakayama et al., 2008). A few recent neuroimaging studies supported the fundamental roles of these higher-level motor cortices of motor imagery. A graph-theory analysis of connectivity during motor imagery identified the premotor cortex being the key node of motor imagery (Xu et al., 2014). This finding is consistent with a proposal that a part of the premotor cortex bridges cognitive sectors and motor sectors of the brain (Hanakawa, 2011). Another study compared imagery and execution of grasping and hand rotation tasks, and examined which motor areas showed the best predictive value differentiating the grasping and rotation tasks (Park et al., 2015). The results of this study showed that M1 and supplementary motor areas had the best predictive value during movement and imagery, respectively. Kasahara and colleagues (2015) explored the brain structural signature of performance of BCI based on motor imagery. BCI performance was correlated with gray matter volumes of premotor and supplementary motor areas. Together, neuroimaging studies with modern technology further supported the significance of premotor and supplementary motor areas for motor imagery.

4.3. Posterior parietal cortex

Evidence strongly points to the significance of the posterior parietal cortex for motor imagery. Many neuroimaging studies with various motor imagery tasks have demonstrated activity in the posterior parietal cortex (Ehrsson et al., 2003; Gerardin et al., 2000; Hanakawa et al., 2003, 2008; Iseki et al., 2008; Naito et al., 2002a). Neurophysiology studies from non-human primates and humans indicate abundant neural information representing a planning state of movement (Affaloro et al., 2015; Cui and Andersen, 2011). Strong evidence is available from lesion studies as well. Patients with damages to the posterior parietal cortex are impaired in accurately imagining movements. Such patients may be unaware of executing movement when asked to imagine it (Schwoebel et al., 2002). Patients with parietal lesions cannot predict their motor performance through motor imagery. Specifically, such patients may overestimate or underestimate the times necessary to perform movement tasks when asked to predict them (Sirigu et al., 1996). This sharply contrasts to outcomes from a precentral motor cortical dysfunction, resulting in impaired movement performance, but a preserved ability to estimate motor performance through mental imagery (Sirigu et al., 1995). Other sensory areas are also shown in relation with mental imagery involving the body. Vibratory stimuli to muscle tendons given at specific frequencies induce illusory perception of kinesthesia and activate the primary somatosensory areas as well as M1 (Naito et al., 2002b, 2011). Listening to sounds of footsteps induces activity in the posterior superior temporal sulcus (Bidet-Caulet et al., 2005). This activity can be interpreted as representing visual motion analysis based on auditory information because the posterior superior temporal sulcus plays an essential role in visual motion analysis (Howard et al., 1996). A nearby multiple-sensory processing area, the temporoparietal junction, has been implicated in the out-of-body experience, which is an illusion of “the self-located in a second body that hovers above the physical body” (Blanke et al., 2005; Ionta et al., 2011). The extraspatial body area is proposed to be selective for visual processing of static and moving imagers of the human body (Downing et al., 2001). Types of virtual sensory modalities associated with motor imagery would substantially change the activity of these sensory associated cortices. Systematic exploration of the modalities would be warranted to fully understand the relative significance of each area for the motor imagery factors.

4.4. Prefrontal areas

Frontal cognitive regions are also reported in neuroimaging studies of motor imagery. Such regions may be relevant to suppressing overt movement during motor imagery. The ventral prefrontal cortex and the anterior cingulate cortex were reported to be involved in the suppression of movement at a preparation...
stage of movement (Krams et al., 1998). This is consistent with findings from a TMS experiment in which the participation of the prefrontal cortex is shown in the inhibitory control of movement (Duque et al., 2012). The role of the premotor cortex is also indicated in the inhibitory control of movement or “impulse control” (Duque et al., 2012; Kroeger et al., 2010). Those areas such as the prefrontal cortex, anterior cingulate cortex, and premotor cortex are the ones most frequently reported to be activated during motor imagery. Future studies are necessary to disentangle brain activity for motor imagery and brain activity for motor inhibition.

4.5. Subcortical areas

Motor imagery consistently recruits subcortical motor areas such as the basal ganglia and cerebellum. Although the roles of these subcortical areas for motor imagery remain unclear, it is likely that the contribution of these areas to motor imagery would be through networks with cortical motor areas. Interestingly, motor imagery is slowed in patients with Parkinson’s disease (Dominey et al., 1995), meaning that the basal ganglia probably modulates parameters such as a speed rather than contents of motor imagery. The cerebellum has been suggested to process efference copy from the motor cortex, thereby providing a basis of mental simulation (Grush, 2004).

5. Applications to rehabilitation and brain–machine–computer interfaces (BMIs/BCIs)

Motor imagery has been a promised neuro-rehabilitation technique (Sharma et al., 2006). This expectation seems reasonable, considering the shared neural mechanisms between motor imagery and movement execution. Put simply, an idea behind this is that it may be possible to train the motor representations in the brain through mental practice of movements. A few case series with a small number of stroke patients have provided preliminary evidence for improvement of clinical outcomes and neuroimaging observations (Butler and Page, 2006; Page et al., 2009). Moreover, two randomized controlled trials combining motor imagery practices and conventional physiotherapy showed results pointing toward the add-on effects of motor imagery training (Liu et al., 2009; Page et al., 2007). Despite these promises, a recent randomized controlled trial with a larger cohort than before failed to find the therapeutic benefit of mental practice of movements in patients within 6 months following stroke (Ietswaart et al., 2011). This study included three groups receiving different interventions: motor imagery, visual imagery, and standard care. Although all groups showed improvement of outcome measures, there were no differences in improvement across the three groups. Hence, it remains to be seen if the motor imagery technique really has therapeutic effects in comparison with other types of interventions. There are many issues to be considered for future clinical trials: factors contributing training effects, patient selection, a way to integrate motor imagery with conventional physiotherapy, and so forth (Malouin et al., 2013). Exploration of the factorial categories of motor imagery from previous studies may provide further insights for future trials.

The usefulness of motor imagery for neuro-rehabilitation likely depends on how motor imagery is implemented into rehabilitation. One of the technical challenges is to obtain an objective measure of motor imagery performance to monitor task competence. To objectively measure task performance of motor imagery, previous studies proposed mental chronometric methods (Sirigu et al., 1996; van der Meulen et al., 2014), speed-accuracy tradeoff (Decety and Jeannerod, 1995), and the last tapped finger of an imaginary sequential finger tapping task (Hanakawa et al., 2003, 2008). However, recent developments in neuro-engineering have made possible online monitoring of motor imagery performance on the basis of neuro-feedback, that is, a type of BMIs/BCIs. Many BMIs/BCIs use changes of alpha- or beta-band electroencephalographic (EEG) oscillations at central electrodes (often called mu rhythm or sensorimotor rhythm). Sensorimotor rhythms are exaggerated at rest and reduced during movement execution and imagery (event-related desynchronization or ERD). In most BMIs/BCIs, subjects are asked to use motor imagery to induce ERD (Kasahara et al., 2015; Wolpaw and McFarland, 2004), so BMIs/BCIs can detect motor intentions. Thus, the level of ERD is usually used as an index of how a subject is engaged in a motor imagery task. Alternatively, motor imagery of feet is reported to induce beta-band event-related synchronization (ERS) in patients with lower limb amputees, showing a differential degree of neuromodulatory effects by transcranial direct current stimulation between amputees and healthy controls (Takeuchi et al., 2015). Thus, if motor imagery evokes ERD or ERS on EEG recordings may differ, depending on the effector of use and its physical condition. In any event, BMIs/BCIs offer visualization of the level of ERD/ERS reflecting performance, so that a subject can modulate their brain activity online (i.e. neuro-feedback). BCI- or neurofeedback-based neuro-rehabilitation is a new promising area of research (Pichiorri et al., 2015; Ramos-Murguialday et al., 2013; Shindo et al., 2011). Similarly, hemodynamic signal changes with motor imagery can be detected with real-time fMRI or functional near-infrared spectroscopy (NIRS). Mihara and colleagues (2013) used hemodynamic signals from supplementary motor areas for neuro-feedback signals during a motor imagery task of distal upper limb. A post-stroke patient group receiving relevant feedback showed significant improvement in clinical scores of finger/hand movements in comparison with a control group receiving random feedback signals.

6. Conclusion

Interventions with motor imagery, including BMIs/BCIs, may become a mainstream of motor imagery studies in the near future. For both sports training and neuro-rehabilitation, it is important to take into account the factors of motor imagery summarized here and understand how to design motor control stages and virtual sensory modalities in motor imagery interventions. The sensory modality of choice would be the first-person perspective kinesthetic-dominant imagery, which appears to work better in re-organizing motor-somatosensoory networks than other modalities. However, the selection of motor control stage is not quite straightforward, considering motor imagery may involve motor suppression/inhibition. For boosting strength of large muscles, it is possible that motor execution at their best, not motor imagery per se, most efficiently works in combination with a certain degree of adjunctive mental practice. However, motor imagery may be better suited for dexterous finger/hand movement because individual finger movements most likely require adequate suppression of non-target muscles. Motor imagery-based training may also be beneficial in patients with excessive muscle activity due to spasticity. In conclusion, the use of systematic report and study design according to the analysis of factors of motor imagery (Table 1) should be considered for future studies as well as interventions.

Conflict of interest

The author declares no conflict of interest associated with this manuscript.
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