Neuropsychologia 97 (2017) 56–65

Contents lists available at ScienceDirect

Neuropsychologia

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

Assessing motor imagery in brain-computer interface training: Psychological and neurophysiological correlates

Anatoly Vasilyev[a,*], Sofya Liburkina[a], Lev Yakovlev[a], Olga Perepelkina[a], Alexander Kaplan[a,b]

[a] Lomonosov Moscow State University, Moscow, Russian Federation
[b] Lobachevsky State University of Nizhni Novgorod, Nizhni Novgorod, Russian Federation

ARTICLE INFO

Keywords:
Motor imagery
Brain-computer interface
Transcranial magnetic stimulation
Mu-rhythm
Psychological assessment
Neurorehabilitation

ABSTRACT

Motor imagery (MI) is considered to be a promising cognitive tool for improving motor skills as well as for rehabilitation therapy of movement disorders. It is believed that MI training efficiency could be improved by using the brain-computer interface (BCI) technology providing real-time feedback on person's mental attempts. While BCI is indeed a convenient and motivating tool for practicing MI, it is not clear whether it could be used for predicting or measuring potential positive impact of the training. In this study, we are trying to establish whether the proficiency in BCI control is associated with any of the neurophysiological or psychological correlates of motor imagery, as well as to determine possible interrelations among them. For that purpose, we studied motor imagery in a group of 19 healthy BCI-trained volunteers and performed a correlation analysis across various quantitative assessment metrics. We examined subjects' sensorimotor event-related EEG events, corticospinal excitability changes estimated with single-pulse transcranial magnetic stimulation (TMS), BCI accuracy and self-assessment reports obtained with specially designed questionnaires and interview routine. Our results showed, expectedly, that BCI performance is dependent on the subject's capability to suppress EEG sensorimotor rhythms, which in turn is correlated with the idle state amplitude of those oscillations. Neither BCI accuracy nor the EEG features associated with MI were found to correlate with the level of corticospinal excitability increase during motor imagery, and with assessed imagery vividness. Finally, a significant correlation was found between the level of corticospinal excitability increase and kinesthetic vividness of imagery (KVIQ-20 questionnaire). Our results suggest that two distinct neurophysiological mechanisms might mediate possible effects of motor imagery: the non-specific cortical sensorimotor disinhibition and the focal corticospinal excitability increase. Acquired data suggests that BCI-based approach is unreliable in assessing motor imagery due to its high dependence on subject's innate EEG features (e.g. resting mu-rhythm amplitude). Therefore, employment of additional assessment protocols, such as TMS and psychological testing, is required for more comprehensive evaluation of the subject's motor imagery training efficiency.

1. Introduction

Motor imagery (MI) is defined as an ability of a human brain to resynthesize motor experiences without any overt movements. Such mental representations could both arise subconsciously and be intentionally constructed and manipulated by a subject, which makes MI a versatile and accessible tool for investigating mechanisms of human cognition and motor behavior. As was demonstrated by numerous studies, motor imagery utilizes nearly the same neural substrate as motor execution, which makes it possible to alter motor performance through MI training (or «mental practice») (Zhang et al., 2011). This phenomenon is widely used for learning and improving motor skills in sports (Holmes and Calmels, 2008), surgical training (Cocks et al., 2014) and by musicians (Lotze, 2013).

Over the last decades the possibility of using MI in neurorehabilitation therapy has also been extensively studied (Jackson et al., 2001; Page et al., 2007). Motor imagery is thought to be helpful in treatment of neurological motor disabilities caused by stroke, Parkinson's disease and spinal cord injuries (for review see Dijkerman et al. (2010)). Although the results of these studies are mostly positive so far, the final conclusions about effectiveness of that approach are yet to be determined.

The imagination of movements could be approached differently by practicing subject not only in regard to perspective (first-person, third-person) or modality used (visual, kinesthetic), but also with various mental strategies within same modality. This likely would be reflected

* Corresponding author.
E-mail address: a.vasilyev@anvmail.com (A. Vasilyev).

http://dx.doi.org/10.1016/j.neuropsychologia.2017.02.005
Received 16 October 2016; Received in revised form 10 January 2017; Accepted 3 February 2017
Available online 04 February 2017
0028-3932/

in activation of different neural substrates (Neuper et al., 2005; Voisin et al., 2011) and therefore affect the lesioned brain in different ways. Because of such ambiguity, it is important that some kind of meaningful and objective assessment technique is incorporated in MI training protocols (Thibault et al., 2016), assuring the brain responsiveness to the exercise and, ideally, providing the patient with feedback on his or her imagery effort quality. While several biofeedback techniques have been proposed for assessing and guiding motor imagery using functional magnetic resonance tomography (fMRI) imaging (DeCharms et al., 2004; Yoo and Jolesz, 2002), near-infrared spectroscopy (Mihara et al., 2013), electromyography (EMG) (Lebon et al., 2012; Lotze et al., 1999) and autonomic nervous system responses (Collet et al., 2011), the brain-computer interface (BCI) approach is believed to be the most promising one (Alonso-Valerdi et al., 2015). In BCI the specific brain patterns (usually registered by electroencephalogram – EEG) associated with motor imagery are translated into commands, granting the patient direct intentional control over virtual environment or assistive device (Wolpaw et al., 2002). It has been shown by multiple studies that the subjects are able to adjust their mental imagery strategies in real time using motor imagery EEG-based brain-computer interface (Bai et al., 2014; Neuper et al., 2009). Therefore, the BCI approach provides purposeful and behaviorally convenient way to practice motor imagery in the closed feedback loop (Rossini et al., 2012).

The motor imagery based BCI (MI-BCI) utilizes changes in cortical sensorimotor rhythms (SMR) – most commonly the suppression (or event-related desynchronization – ERD) of EEG 10-Hz frequency component (mu-rhythm), associated with processing of various sensorimotor events, including motor imagery. Although registered sensorimotor rhythm ERD is considered to be an important neurophysiological correlate of the cortex functional state, its non-specificity to the various motor tasks (Llanos et al., 2013) and quantitative instability across human population (Blankertz et al., 2010) challenge the idea of using such reactions as an indicator of potential training effectiveness or motor imagery effort quality. Indeed, some of the motor impairments are known to lead to attenuation or disappearance of SMR reactivity (Lopez-Larraz et al., 2015), while the ability to perform motor imagery of those patients is still retained (Johnson, 2000). Moreover, the noticeable portion of healthy subjects do not display any ERD reaction during motor imagery and therefore are considered to be unable to operate in brain-computer interface (referred to as "BCI-illiteracy", (Allison and Neuper, 2010)).

It is not clear, whether people with absent ERD could benefit from motor imagery, and, if they do, what metrics should be used to quantify the neurophysiological impact of the exercise. A large number of transcranial magnetic stimulation (TMS) studies have shown that the motor imagery produces an increase in cortical excitability in the motor cortex corresponding to the muscle involved in imagined movement (Hashimoto and Rothwell, 1999). It is also believed that corticospinal excitability increase would be the most desired (Cicinelli et al., 1997) effect of the MI training in rehabilitation therapy. Hence, TMS measurement could be considered as a candidate for a reliable and meaningful metric for the motor imagery assessment.

The psychological assessment represents probably the most conventional and well-validated method of measuring motor imagery. It is usually aimed at collecting introspective reports on vividness of subjects' imagery and is performed via questionnaires and interview with the subjects. Although the introspective methods often hold large amount of subjectivity, they are convenient to use and are shown to be well-correlated with several objective physiological measures (Marchesotti et al., 2016; Williams et al., 2012) or complement the latter (Collet et al., 2011). Most commonly, the clinical motor imagery research methodologies include assessments of MI-ability with questionnaires as an inclusion criterion (Malouin et al., 2004). Cases of using psychological measurement for evaluation of the results are also recorded (Wondrusch and Schuster-Amft, 2013).

As it was demonstrated by several studies, systematic exercising with MI-BCI modifies subject's physiological responses to imagery itself as seen on EEG (Toppi et al., 2014), fMRI and excitability measures (Mokienko et al., 2013) indicating the presence of a training effect. Motor imagery training is also known to lead to short- and long-term functional reorganization of motor cortex (for review see (Di Rienzo et al., 2016)) affecting motor performance and cause improvement of cognitive sphere in elder subjects (Gomez-Pilar et al., 2016).

In this study, we used a multimodal approach to the assessment of motor imagery, attempting to establish the connection among its neurophysiological and psychological correlates. For that purpose, we used various techniques of psychological (interview, questionnaires) and neurophysiological (EEG patterns analysis, corticospinal excitability measurement, BCI performance) assessment of motor imagery in healthy BCI-trained volunteers. To the knowledge of the authors such multimodal experimental design has never been implemented. We believe that comparison of psychological and neurophysiological correlates presented here will help to better understand the nature of MI, decipher its underlying neural processes. Our results may have important implications for further research of mental imagery in clinical practice.

2. Method

2.1. Subjects and sessions

19 healthy human subjects (7 females) aged 19–27 participated in the experiment. There were no exclusion criteria other than the neurological health. Hand dominance was assessed with the Edinburgh handedness questionnaire (Oldfield, 1971): 16 of the subjects were right handed (score +0,875 ± 0,04), two – left handed (score −0,9 ± 0,00) and one – bimanual (score +0.1)). All participants gave their informed consent. The experimental procedures were designed and carried out in accordance with Declaration of Helsinki and were approved by the Lomonosov Moscow State University Ethical Committee.

The study had a multi-day design and was comprised of five distinct MI-training protocols (No. 1–5) and psychological assessment protocols (ψ_1, ψ_2). To ensure equal effective amount of training, a number of participants had to repeat some of the sessions (e.g. «1, 2, 2, 3 $_{+}\psi_1$, 4, 5, ψ_2»), resulting in increased number of attended days for those subjects: four with 6d, two with 7d and one with 8d. Any session protocol was subject to repetition if any of the following criteria were met: (1) presence of excessive exhaustion of the subject during session (measured by «current mood» questionnaire, see Section 2.6); (2) substantial drop in BCI performance comparing to the previous session; (3) inability to finish all planned recordings due to either reason.

The sessions' protocols were designed with progressive complexity. The first session was dedicated to learning the correct movements, familiarization with the concept of imagery as well as with the brain-computer interface setup. The objective of the second and the third sessions' protocols for subjects was to find the most effective imagery strategy with the guidance of experimenter and BCI. After successful completion of protocol No. 3 the first psychological assessment was conducted (see Section 2.6). The fourth session included mostly BCI trials with visual feedback. The imagery strategy was kept unformed during No. 4–5 according to the subject's preferred technique (see Section 2.2). The fifth session resembled protocol No. 4 but with half as much trials, followed by the TMS measurement. The second psychological assessment was done in separate day week apart from the last session. No more than three motor imagery training sessions (typically, two) were done in between the two psychological assessments. The whole study took 5–7 weeks for each subject to complete.