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Research Report

Imagery of motor actions: Differential effects of kinesthetic and visual–motor mode of imagery in single-trial EEG

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Abstract

Single-trial motor imagery classification is an integral part of a number of brain–computer interface (BCI) systems. The possible significance of the kind of imagery, involving rather kinesthetic or visual representations of actions, was addressed using the following experimental conditions: kinesthetic motor imagery (MIK), visual–motor imagery (MIV), motor execution (ME) and observation of movement (OOM). Based on multi-channel EEG recordings in 14 right-handed participants, we applied a learning classifier, the distinction sensitive learning vector quantization (DSLVQ) to identify relevant features (i.e., frequency bands, electrode sites) for recognition of the respective mental states. For ME and OOM, the overall classification accuracies were about 80%. The rates obtained for MIK (67%) were better than the results of MIV (56%). Moreover, the focus of activity during kinesthetic imagery was found close to the sensorimotor hand area, whereas visual–motor imagery did not reveal a clear spatial pattern. Consequently, to improve motor-imagery-based BCI control, user training should emphasize kinesthetic experiences instead of visual representations of actions.
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1. Introduction

The use of mental imagery of motor behavior plays an important role in motor skill learning [11] and rehabilitation [39]. Aside from these classical applications, motor imagery, defined as mental simulation of a movement [5,13], has been shown to represent an efficient mental strategy to operate a direct brain–computer interface (BCI) [22]. For the latter application, e.g. the control of an external device based on brain signals (i.e., EEG signals), it is essential that imagery-related brain activity can be detected in real time from the ongoing EEG. The main goal of this research work is to establish an EEG-based communication system that should provide an alternative communication or control channel for patients with severe motor impairment [40].

It has been shown that mental imagery of motor actions can produce replicable EEG patterns over primary sensory and motor areas [2,21]. As an example, imagery of hand movements results in desynchronization of mu (8–12 Hz) and central beta rhythms (13–28 Hz), very similar to planning and execution of real movements [17]. It is even possible to distinguish between imagined right and left

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hand movements based on single-trial EEG signals [19,22,24]. These data strongly indicate a type of readiness or presetting of neural networks in sensorimotor areas during mental simulation of movement. Further evidence in favor of matching cortical activity in the contralateral hand area during execution and imagination of hand movement comes from DC potential measurements [2] and dipole source analysis of electric and magnetic fields [14].

Even though it has been well documented that imagination of simple movements elicits predictable changes in the sensorimotor mu and beta bands, which are very stable over time (i.e., small intra-subject variability), there are also conflicting results of a portion of participants, who do not show the expected imagery-related EEG changes [22]. Moreover, a diversity of time–frequency patterns (i.e., high inter-subject variability), especially with respect to the reactive frequency components, was found when studying the dynamics of oscillatory activity during movement imagination [17,25,38].

The observed individual differences in imagery-related EEG changes may be explained by varieties of motor imagery, as described by Annett [1]. In case that there is no specific instruction, the subject may, for example, either imagine self-performed action with 'interior view' or, alternatively, imagine seeing himself or another person performing actions with an exterior view (i.e., 'mental video') [4]. Whereas the first type of imagery is supposed to involve kinesthetic experiences [34], the second case may be primarily visual in character. Based on the general idea that imagining is functionally equivalent to and may share some of the brain processes associated with real perception and action [1,35], the different ways how subjects perform motor imagery are very likely associated with dissimilar electrophysiological activation patterns (i.e., in terms of time, frequency and spatial domains).

In the present study, we investigated the EEG patterns sensitive to different types of motor imagery. In particular, the instruction how to imagine action was varied to create (i) kinesthetic motor imagery (first-person process) and (ii) visual–motor imagery (third-person process). For control purposes, also 'real conditions' were examined, i.e., the execution and visual observation of physical hand movements, respectively. The goal of this study was to identify relevant features of the ongoing multi-channel EEG (i.e., electrode locations and reactive frequency components) that represent the specific mental processes. In order to determine the relevant features for recognizing the respective mental states, a neural network classifier, the distinction sensitive learning vector quantization (DSLVQ) [29] algorithm, was used. This method uses a weighted distance function and adjusts the influence of different input features (e.g. frequency components) through supervised learning.

2. Methods

2.1. Subjects

Fourteen healthy volunteers, aged 18–53 years (mean = 26.2, SD = 8.3), participated in the study. All were right-handed, without any medical or psychological diseases and/or medication and had normal or corrected to normal vision. The participants gave informed consent after the experimental procedure had been explained to them and received a small fee for their participation.

2.2. Experimental tasks and procedure

During the experiment, the participants were sitting in a comfortable armchair in front of a 17″ monitor at a distance of about 1.3 m, in an electrically shielded recording room. Four experimental tasks were performed during EEG recording. Before each task condition, verbal instructions were given, and a number of training trials were presented to the participants until they felt confident enough that they could perform the respective task.

ME	Motor execution: subjects held a small ball in their right fist, while their forearm rested on the arm rest. They were instructed to perform continuous hand movements by clenching softly the ball during indicated time periods as described below.
MIK	Imagery of hand movement ('kinesthetic'): subjects were instructed to imagine clenching softly a ball with their right hand, while their arm rested relaxed on the arm rest. They were asked to imagine the kinesthetic experience of movement while avoiding muscle tension.
OOM	Observation of hand movement: subjects observed grasping movements of an animated (right) hand. They were instructed to sit relaxed and watch the presentation on the monitor in front of them.
MIV	Imagery of hand movement ('visual–motor'): subjects were instructed to visualize right hand movements; specifically, they were asked to create a 'mental video' of the movements of the 'alien' hand they watched in the previous condition.

Besides the specific task instructions, the participants were asked to sit relaxed with eyes open and to avoid any eye movements and body movements other than requested. The correct task execution was monitored using a video system installed in the recording compartment. Subjective ratings of the vividness of the imagined movements were obtained by verbal report after completion of the respective task.

For the visual stimulus presentation (in condition OOM), a digitized video sequence of a realistic (animated) hand was presented on the screen. The animated hand was a right (open) hand which appeared at the beginning of the trial (i.e., at second 2) and remained static for 1 s. Then, it began to close (make a fist) and to open again. This action was

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