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# Real movement vs. motor imagery in healthy subjects

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## ABSTRACT

Motor imagery tasks are well established procedures in brain computer interfaces, but are also used in the assessment of patients with disorders of consciousness. For testing awareness in unresponsive patients it is necessary to know the natural variance of brain responses to motor imagery in healthy subjects.

We examined 22 healthy subjects using EEG in three conditions: movement of both hands, imagery of the same movement, and an instruction to hold both hands still. Single-subject non-parametric statistics were applied to the fast-Fourier transformed data.

Most effects were found in the $\alpha$- and $\beta$-frequency ranges over central electrodes, that is, in the $\mu$-rhythm. We found significant power changes in 18 subjects during movement and in 11 subjects during motor imagery. In 8 subjects these changes were consistent over both conditions. The significant power changes during movement were a decrease of $\mu$-rhythm. There were 2 subjects with an increase and 9 subjects with a decrease of $\mu$-rhythm during imagery.

$\alpha$ and $\beta$ are the most responsive frequency ranges, but there is a minor number of subjects who show a synchronization instead of the more common desynchronization during motor imagery.

A (de)synchronization of $\mu$-rhythm can be considered to be a normal response.

## 1. Introduction

Motor imagery is a frequently used paradigm in several fields of research. Most studies involving tasks with motor imagery can be found in the field of brain–computer-interfaces (BCI) (see Nicolas-Alonso and Gomez-Gil, 2012, for a review). In healthy subjects, it is possible to provoke activations of specific brain regions or specific activation patterns as responses to motor imagery (Pfurtscheller et al., 2006a, 2006b, Birbaumer, 2009). These activations can be detected with an adequate sensor. In BCI the data acquisition is often done with electroencephalography (EEG). The detected signals are then used to control simple devices or tools.

Another application for motor imagery is in disorders of consciousness, in which the task is used to elicit voluntary brain activation, in order to distinguish patients in a locked-in-like state from unresponsive patients with disorders of consciousness (DOC) (Bekinschtein et al., 2009; Boly et al., 2007; Cruse et al., 2011; Goldfine et al., 2011; Monti et al., 2009, 2010; Owen et al., 2006; Schnakers et al., 2008, 2009). Most studies investigating motor imagery in DOC were performed with functional Magnetic Resonance Imaging (fMRI) (Monti et al., 2009, 2010; Owen et al., 2006). Goldfine et al. (2011) suggest that examining motor imagery in DOC using EEG has several advantages over fMRI, e.g., the EEG can be recorded bedside, it is possible to perform with ferromagnetic implants, and it is not as prone to movement artifacts as fMRI. The authors examined EEG power changes in motor imagery and spatial navigation tasks in healthy subjects and patients with severe brain injury and found significant responses in patients. Cruse et al. (2011) applied motor imagery in patients with DOC and reported that three of 16 patients with unresponsive wakefulness syndrome showed significant motor-imagery related activation. Most importantly, the authors separated command-specific from imagery-related brain responses.

In BCI research, a large number of researchers concentrate on the fast and accurate classification of brain responses in motor imagery tasks. The field of DOC-research could benefit from the development of sophisticated algorithms and tools by BCI-scientists. However, the results from the large amount of studies in BCIs cannot be translated one to one to DOC research. An obvious difference between BCI and DOC research is the training. It is straightforward to train patients

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with tetraplegia in the use of a BCI, but the same procedure cannot be applied in a patient who cannot respond at all. If we cannot train the patient, we must deal with what is exhibited without any training. Therefore, we are interested in the consistency of EEG-brain responses to tasks with voluntary brain activation among healthy subjects. Only on the background of natural variance can the responses of patients with DOC be interpreted adequately.

The earliest assessed motor-related EEG-biomarkers are modulations of power in specific frequency bands. Müller-Putz et al. (2005) trained a patient to generate distinctive EEG-patterns by the imagination of movements of his paralyzed left hand. The resulting power decreases were classified by the BCI and were used to control a neuroprosthesis for grasping actions. Today, frequency analysis is combined with modern algorithms such as independent component analysis (Wang and James, 2007). The reason for the permanence of the frequency-issue may be the prominent effect in the $\mu$-rhythm; that is, in the alpha ($\alpha$) range between 8 and 13 Hz over the sensorimotor cortex (Pfurtscheller et al., 2006a). Pineda (2005) suggests that the $\mu$-rhythm reflects the translation of hearing an instruction into performing the required action. This circumscription is well in line with the behavior of this frequency. The $\mu$-rhythm typically desynchronizes 2 s before movement onset, but motor imagery can also invoke the same suppression response (Pineda, 2005). In addition, the beta ($\beta$) range between 13 and 30 Hz is known to desynchronize during real movement and motor imagery (Pfurtscheller et al., 2006b).

In our recent research we found that brain responses show a large interindividual variability (Höller et al., 2011a, 2011b). Also, the $\mu$-rhythm shows typical and atypical activation patterns (Pineda, 2005). This variance may disturb the examination of brain reactivity in patients with DOC. Goldfine et al. (2011) applied frequency analysis to motor imagery data of 5 healthy subjects, one patient with locked-in syndrome, and 2 patients in a minimally conscious state. They found significant power changes in one patient in a minimally conscious state and in the patient with locked-in syndrome. These changes differed from the patterns found in healthy controls. However, there were considerable inter-individual differences between healthy controls as well. Cruse et al. (2011) reported that for 9 out of 12 healthy subjects the classification of motor imagery succeeded. The other three healthy subjects did not reach significant classification accuracies.

Before applying modern algorithms to the motor-imagery data of patients with DOC, we wanted to examine if there were reliable patterns of brain activity during the chosen motor task and the respective imagery task in healthy subjects. In the present study, we used a simple motor-imagery task and applied single-subject statistics to examine frequency-characteristics. By analyzing on a single-subject level we address the question of whether there are universal response-patterns, or if they differ between subjects. In addition, by comparing real movement with motor imagery, we examine the consistency between the patterns of brain activity in these tasks. In contrast to previous work (for example, Goldfine et al., 2011; Pfurtscheller et al., 2006a, note that most BCI-studies rely on event related changes, i.e., calculate power changes in relation to a pre-stimulus baseline), we compare the activation during task performance with a specific resting task. The resting condition is preceded by a hand-related instruction (i.e., to hold the hand firm). In such a way the subjects have to pay attention to the hands during rest. Thus, we can control for speech-related activations, which are common in patients with DOC and are not necessarily related to awareness (Coleman et al., 2007; Crone et al., 2011).

## 2. Materials and methods

### 2.1. Subjects

A sample of 22 high school graduated subjects (age: 20–26 years; mean = 22.86 years; SD = 1.81; 6 male) was recruited and tested. None of the participants reported any history of neurological or psychiatric diseases, nor were they receiving any psychoactive medication. Informed consent was obtained from each subject according to the ethical guidelines of the Declaration of Helsinki. All subjects were remunerated for their expenditure of time.

### 2.2. Experiment

The experiment consisted of three conditions. In the movement-condition the subjects were asked to open and close both hands. A second condition, the imagery-condition, consisted of imagining the same movement kinesthetically. Finally, a third condition consisted of no movement and no imagery; as such, this was the resting condition. The resting condition was a special type of task which was preceded by the instruction to hold both hands firm. To ensure that the subjects performed the task in the movement- and the imagery-condition during a certain period of time, they were instructed to perform the task while hearing a tone sequence of 2 tones. Both tones were alternatingly recurring once per second. Thus, the subjects opened and closed their hands once per second. The instructions had durations of 6, 6.5, and 9.5 s for the rest, move, and imagery conditions, respectively. After each instruction, there was an interval of 5 s during which the subjects were expected to follow the instruction (i.e., to move in the movement-condition, to imagine a movement in the imagery-condition, and to hold the hands firm in the rest-condition). Instructions were presented verbally and binaurally through earphones using Presentation software (Neurobehavioral Systems, version 12). The auditory material was recorded and processed with Audacity (version 1.2.6). The instructions were normalized to an equal sound level. There were 24 trials for each condition. To avoid expectation effects, stimuli were presented in a pseudo-randomized order. Subjects were asked to look straight ahead during the experiment.

### 2.3. Data registration

EEG-data was recorded using a BrainCap with a 10-20 system and a Brain-Amp (Brain Products GmbH, Germany) 16-bit ADC amplifier. The sampling rate was 500 Hz. Of the 32 recorded channels, 2 were used to monitor the left and right horizontal electrooculograms. One was used to monitor lower-site vertical electrooculogram. Two were positioned at the mastoids for re-referencing purposes to remove the bias of the original reference, which was placed at Fcz. The other electrodes were Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T7, T8, P7, P8, Fz, Cz, Pz, FC1, FC2, CP1, CP2, FC5, FC6, CP5, and CP6. Data analysis was conducted for data collected from the electrodes F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, P7, P8, Fz, Cz, and Pz. Impedances were kept below 10 kΩ.

### 2.4. Data preparation

Data pre-processing was done with Brain Vision Analyzer (Version 1.05.0005, Brain Products GmbH). First, mastoid electrodes were used to build a new averaged reference for all other channels. To obtain a bipolar vertical electrooculogram, the average of Fp1 and Fp2 was used as a reference for the lower-site vertical electrooculogram. Left and right horizontal electrodes formed a bipolar configuration of the horizontal electrooculogram. To reduce noise, Butterworth Zero Phase Filters from 1 to 48 Hz (time constant 0.1592 s, 48 dB/oct) were applied.

Independent component analysis (ICA) was applied, since this procedure has been shown to effectively detect, separate, and remove ocular, muscular, and cardiac artifactual sources in EEG data (Makeig et al., 1996; Jung et al., 1998, 2000). The ICA was calculated on all channels, including the prepared electrooculographic channels. After visual inspection of the ICA components, those components containing ocular or muscle artifacts were determined and removed by performing the corresponding ICA back-transformation.