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Detection of attempted movement in minimally conscious state patients via electroencephalography: Evaluation of an auditory paradigm in healthy subjects

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Abstract

The aim of this study was to test an auditory paradigm on healthy subjects for further studies with minimally conscious state (MCS) patients. This paradigm uses electroencephalography (EEG) to detect attempted movements. As analogy for attempted movement on MCS patients, executed movement of healthy subjects was used. A total of 12 healthy subjects participated in the task which consisted of 80 trials for hand and foot movement, respectively. The data was analyzed by detecting the movement-related cortical potential (MRCP) and calculating time-frequency plots and power spectra. On the basis of those findings, the suitability of the paradigm could be evaluated. In conclusion most of the subject's measurements lead to usable outcomes. Therefore, the paradigm fulfills its purpose of providing an approach to detect movement related EEG patterns. The aim of further studies is to test the paradigm on MCS patients, find out about their state of consciousness and perform online classification to provide a communication channel.

Kurzfassung

Das Ziel dieser Studie war, ein auditorisches Paradigma an gesunden Probanden für weitere Studien an Patienten im minimally conscious state (MCS) zu testen. Das Paradigma verwendete Elektroenzephalographie (EEG) um versuchte Bewegungen zu detektieren. Als Analogie für eine versuchte Bewegung bei MCS Patienten, wurde das Paradigma bei gesunden Freiwilligen mit ausgeführten Bewegungen durchgeführt. Insgesamt haben an der Studie 12 gesunde Testpersonen teilgenommen und führten jeweils 80 Hand- bzw. Fußbewegungen aus. Die anschließende Analyse der Daten geschah durch Ermittlung von sogenannten 'movement-related cortical potentials' (MRCP) und der Darstellung von Zeit-Frequenz Grafiken sowie von Leistungsspektren. Anhand der erhaltenen Ergebnisse konnte untersucht werden, ob das Paradigma seinen Zweck erfüllt und für weitere Messungen geeignet ist. Zusammengefasst war die Mehrheit der Ergebnisse zufriedenstellend. Somit erfüllt das Paradigma die Anforderungen und ermöglicht den Weg für zukünftige Studien. Das Ziel weiterführender Studien ist es, das in dieser Arbeit beschriebene Paradigma an MCS Patienten zu testen, dadurch deren Bewusstseinszustand besser einstufen zu können und in weiterführenden Untersuchungen eine Online-Klassifizierung zu implementieren.

Acknowledgements

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Special thanks to all volunteers who participated in the study.

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List of acronyms

BCI	Brain computer interface
CAR	Common average reference
EEG	Electroencephalography
ERD	Event-related desynchronization
ERS	Event-related synchronization
MCS	Minimally conscious state
MRCP	Movement-related cortical potential
VS	Vegetative state

1 Introduction

Due to improving emergency therapy and intensive-care medicine, the number of people who survive severe brain injuries increases. Some of the patients do not recover fast and go through different stages to get back their consciousness fully or partially [1]. These states of consciousness have to be distinguished and are very difficult to define and especially to diagnose [2]. These states are divided into coma, unresponsive wakefulness syndrome (UWS) [3] and minimally conscious state (MCS). Before going into detail, the term consciousness has to be specified. There are two main components in which consciousness can be divided: Arousal describes the wakefulness of a person, whereas awareness means to be aware of the environment and oneself [4].

Coma is characterized by the complete loss of both wakefulness and awareness. These patients have no function of the arousal system anymore and therefore show no reaction on vigorous stimuli [1][2][4].

Patients in an *UWS* are awake, but are unaware of their selves and the environment. These patients show spontaneous eye or respiratory movements. As soon as the visual fixation is repeatable and steady the diagnosis UWS may be not correct anymore [2].

In this case the term *MCS* comes in. Patients in MCS are not able to communicate or interact appropriately. However, they show irregular but repeated signs of partial preservation of their awareness. For instance grabbing things or answering Yes/No-question with a gesture. MCS describes a better condition than UWS and has to be differentiated [1][2][4].

The difficulty of diagnosis and distinction of different states is, that the assessment is mainly based on motor action, which leads to a misdiagnosis if the patient is unable to move, but nonetheless aware [5]. This is where the Brain Computer Interface (BCI) comes into play [6].

A BCI provides the possibility to open a channel between brain and environment. By means of electroencephalography (EEG), brain signals of a person can be measured, processed and interpreted. Different actions generate distinct signals which can be detected by a computer [6][7].

In this study, limb movement was chosen as trigger action. Movements create a special potential in the motor cortex which is called movement-related cortical potential (MRCP) [8]. The same potential is also evoked if patients who are unable to move, try to do so (attempted movement). For this reason an auditory paradigm was created which asks the subject to try to move their feet or hands, while recording an EEG. Afterwards signal processing was applied to analyze the obtained brain signal.

As part of a larger study, the present thesis focused on evaluating the feasibility of this approach in healthy subjects and on optimization of data processing. If registration is successful the study paradigm will then be applied to MCS patients and results will be evaluated. If this can be successfully achieved, the next step is to create a communication channel for MCS patients by implementing online classification.

2 Materials and methods

2.1 Participants

A total of 12 healthy subjects (5 female, 7 male; aged between 20 and 28 years) participated in this study. They had no experience with BCI and were instructed about the task in advance. They attended the study on a voluntary basis and written informed consent was obtained from all study participants. The recordings of three test persons were deficient and therefore had to be excluded from further investigation.

2.2 Recording

The recordings took place in an electromagnetically and noise shielded room to ensure the same conditions for every healthy volunteer. An EEG cap (g.GAMMAcap, g.tec, Graz, Austria) with 16 active electrodes (g.tec, Graz, Austria), which was placed over the motor cortex as shown in Figure 2.1, was used. The ground and reference electrode were located at the electrode positions Fz and A1 (left ear lobe), respectively. The electrodes were connected via a preamplifier (g.GAMMAbox, g.tec, Graz, Austria) to an EEG amplifier (g.USBamp, g.tec, Graz, Austria), which was set up with a chebyshev filter of 8^{th} order between 0.01 and 100 Hz and a notch filter at 50 Hz. The EEG was sampled with 256 Hz. Recording and synchronization of the data was performed by the usage of MATLABR2018a (Mathworks, Massachusetts, USA) and TOBI SignalServer [9].

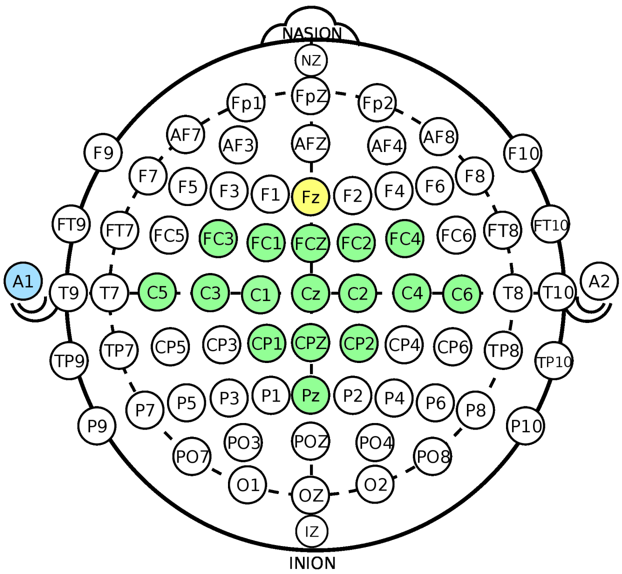

Figure 2.1: Electrode placement. green: measurement; yellow: ground; blue: reference [10]

2.3 Paradigm

The basic idea of the paradigm was to trigger foot and hand movements, which should produce a specific brain signal, the so-called MRCP. To be able to measure and analyze this potential, a large number of trials was needed in order to reduce the background noise [11]. The paradigm needed to be auditory, as MCS patients often suffer from impaired visual function. Therefore all instructions were recorded and reproduced audibly for the measurements via headphones.

The subjects were sitting on a chair with their feet touching the floor and their hands lying relaxed on a table in front of them. The volunteer was asked to perform two basic movements, which were defined in the auditory instruction of the paradigm. The hand movement was defined by clenching both hands into fists and relaxing them afterwards. For foot movement, the subjects had to pull up both feet (keeping heels on the ground) and let them drop back down onto the floor. In order to determine a well-defined start point for movement, the actual cue was defined by the sound of a gong which took 0.4 s long. The sequence of the whole paradigm is shown in Figure 2.2.

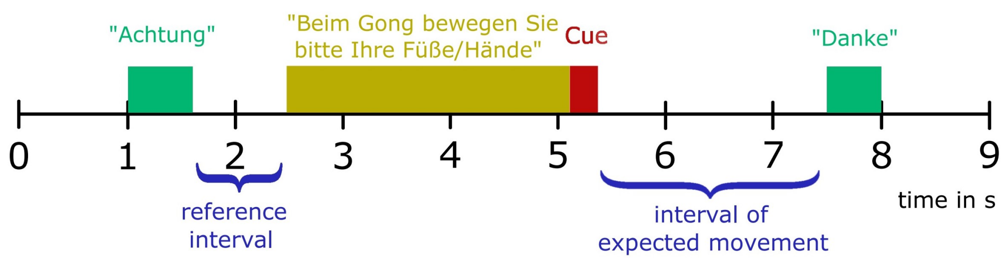

Figure 2.2: Paradigm.

The participants were instructed about the task in advance and drawn attention to multiple artefact sources which should be avoided during the recording time, such as blinking, teeth grinding, swallowing, etc.

Before the very first trial an introduction was played back, in which the test person was prepared for the following task. One run comprised 40 trials, whereof 50% were hand and 50% foot movements respectively in pseudo-randomized order. Overall 4 runs were recorded with short breaks in between, which resulted in 80 trials for each category (hand and foot).

2.4 Data analysis

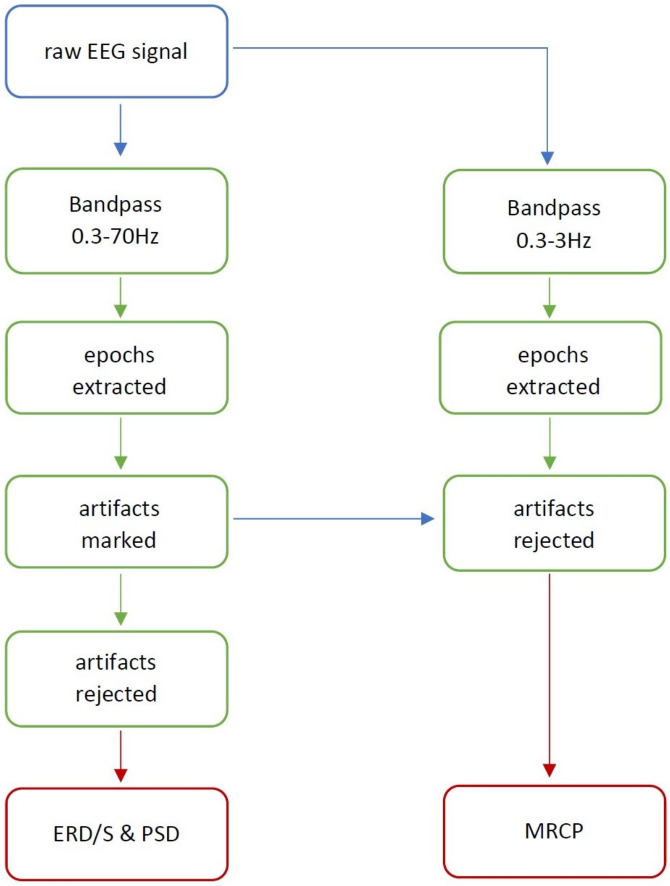

Figure 2.3: Signal processing steps.

The data was filtered by a zerophase bandpass filter between 0.3 and 70 Hz with the EEGLAB [12] function `pop_eegfiltnew.m`. The highpass filter leads to a minimization of mean value fluctuation, which is caused by e.g. sweat.

Afterwards data epochs were extracted from -4 s to 3 s with respect to the cue onset. Artefact detection was performed by marking all artefact tainted trials based on specific parameters: amplitude threshold ($\pm$ 100 μV), abnormal joint probability (four times standard deviation) and abnormal kurtosis (four times standard deviation). On average 24.58 % of the trials were marked and later on rejected.

As mentioned previously, the main interest of this study was to evoke and measure a MRCP. The MRCP is characterized by an increasing negativity of EEG amplitude. This specific potential already starts about 1 s before movement onset and is therefore related not only to the execution, but also planning of a movement. It is characterized by an amplitude between 5 and 30 μV and a frequency range of 0 to 5 Hz [8][11].
Therefore, a zerophase bandpass filter between 0.3 and 3 Hz was applied to the raw EEG data with `pop_eegfiltnew.m`. Afterwards data epochs were extracted and artefact tainted trials were removed. Results were visually assessed and dependent on the subject, outer channels were removed manually for better visualization if necessary. For visualizing the MRCP the mean over all trials was calculated and plotted. As a measure of the mean's precision, the standard error of the mean was plotted additionally.

Further effects of an executed or attempted movement can be seen as a variation of power in frequency bands. Therefore a power decrease or increase relative to a predefined reference interval can be calculated. These changes in power over time are called event-related desynchronization and synchronization (ERD/S) [13]. To illustrate them, time-frequency maps and power-spectra-density plots were computed.

The time region of interest for those plots was defined from 4 s before to 3 s after the cue, because a reference interval where no movement execution is performed was needed. This reference interval was chosen between 3.5 and 2.6 s before cue onset, because this represents the time between 'Attention' and the instruction of limb movement as can be seen in Figure 2.2. The time window in which the movement is expected to happen is defined between 0.4 and 2.2 s after the cue.

For computing the (ERD/S) map and power spectrum, the original, band-pass (0.3 - 70 Hz) filtered, signal was used and artefacts were rejected the same way as described before. ERD/S maps were calculated for a frequency range from 5 to 40 Hz (34 bands with a bandwidth of 2 Hz) and plotted by the EEGLAB [12] functions `calcErdsMap.m` and `plotErdsMap.m`. A significance level of α=0.05 was chosen to enhance only important information. For plotting the power spectra density, the EEGLAB [12] function `spectopo.m` was used with a window size of 256 samples and an overlap of 10 samples. The movement interval was split into to windows of the same size as the reference interval.

An overview of the signal processing steps is shown in figure 2.3.

3 Results

For representative reasons, the results of only one subject are shown. Figures 3.1 to 3.6 all descend from subject S10 and represent acceptable results.

In every plot, the vertical line at t=0 represents the cue onset.

In figure 3.1 the MRCPs of foot and hand movement can be seen.
Figure 3.7 shows a grand average over the means of more subjects. Subjects were chosen based on the acceptable results. For foot movement the subjects S06, S10 and S12 and for hand movement S06, S07, S09, S10 and S12 were selected. Figures 3.2 and 3.8 represent a close-up of the central channels.

In figures 3.3 and 3.4 the ERD/S Maps over all channels are represented. The area between -3.5 s and -2.6 s before cue onset is marked with dashed vertical lines and describes the reference interval. Desynchronization (red) and synchronization (blue) are computed relative to this interval.

Figures 3.5 and 3.6 show the power spectra. The reference curve refers to the time interval between -3.5 to -2.6 s, whereas the movement curves refer to 0.3 to 1.2 s and 1.2 to 2.1 s respectively.

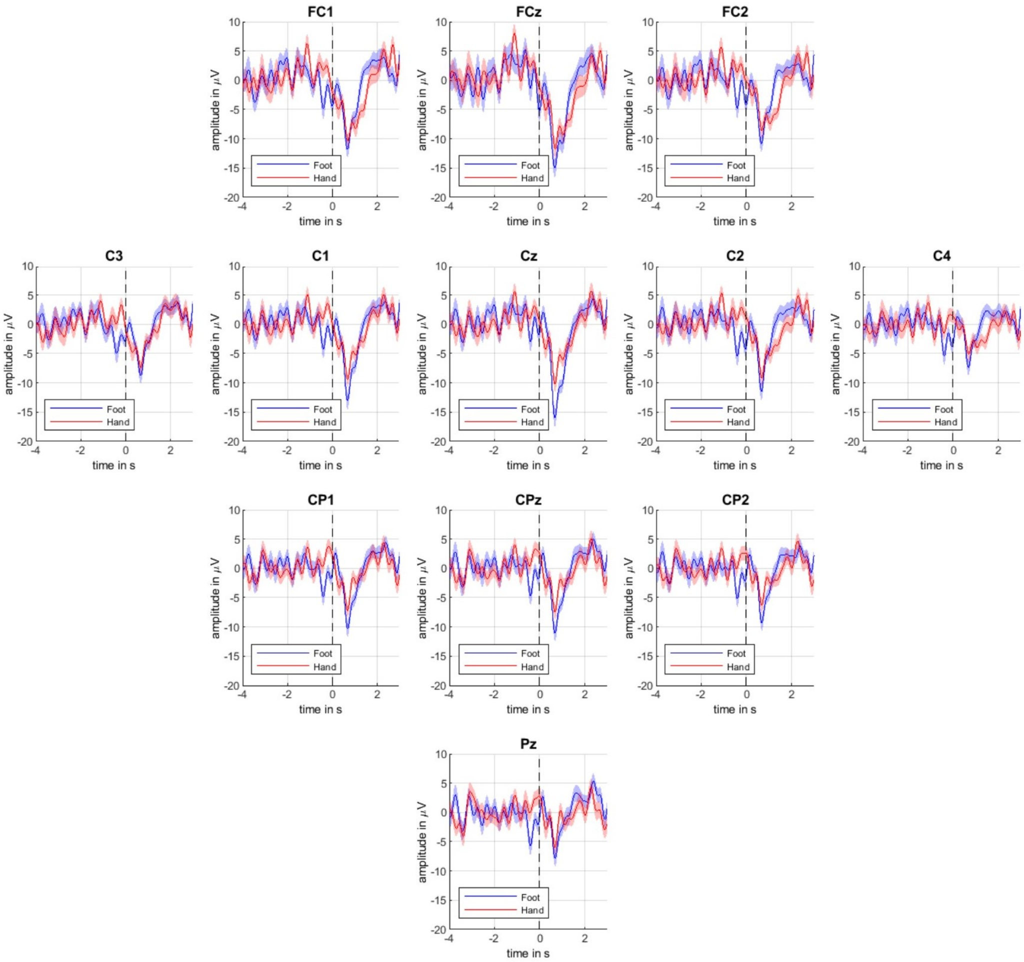

Figure 3.1: MRCP foot and hand. t=0 describes cue onset. Color shaded areas show the standard error of the mean.

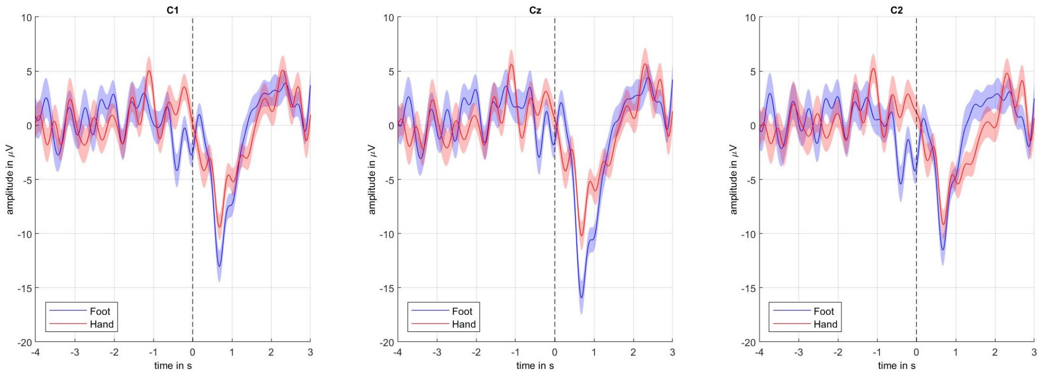

Figure 3.2: MRCP foot and hand: Close-up. t=0 describes cue onset. Color shaded areas show the standard error of the mean.

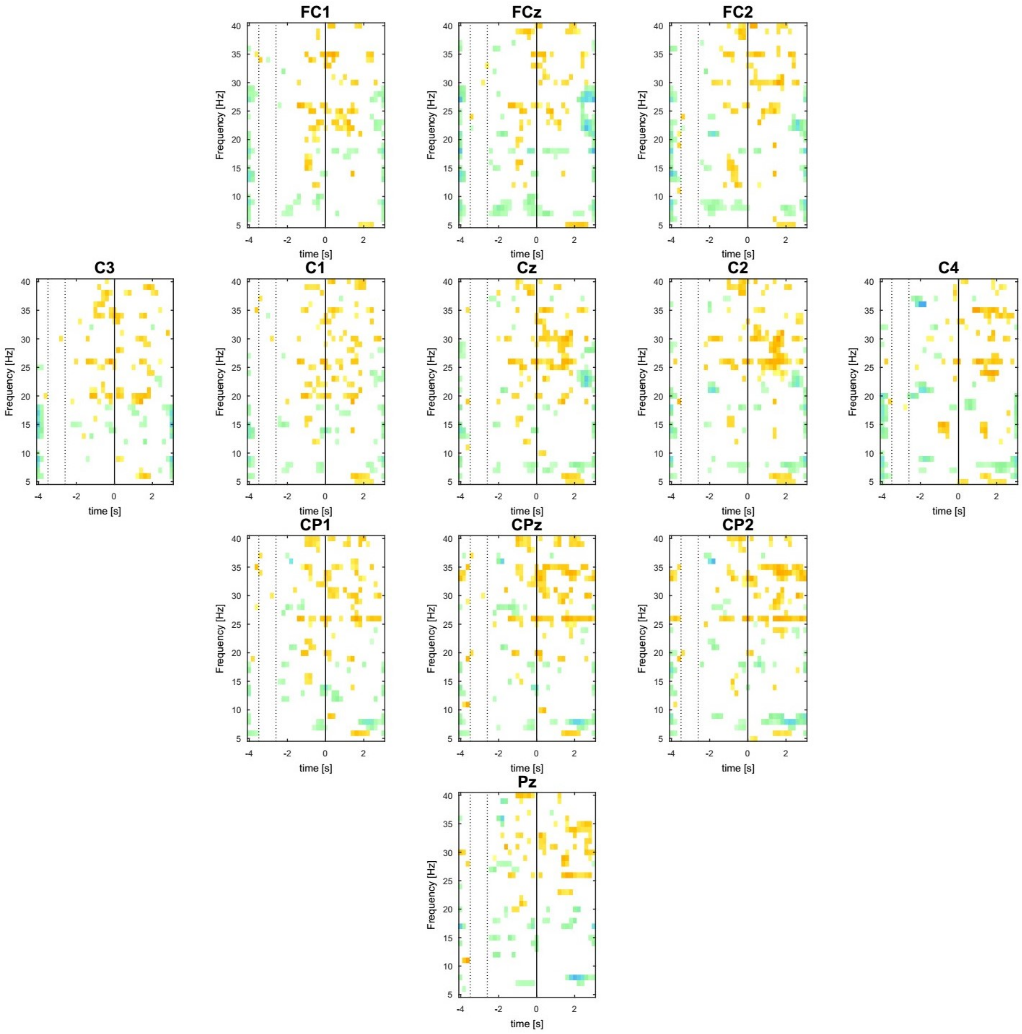

Figure 3.3: ERD/S map foot. t=0: cue onset. reference interval: t=-3.5 s to t=-2.6 s. Significance level: α=0.05

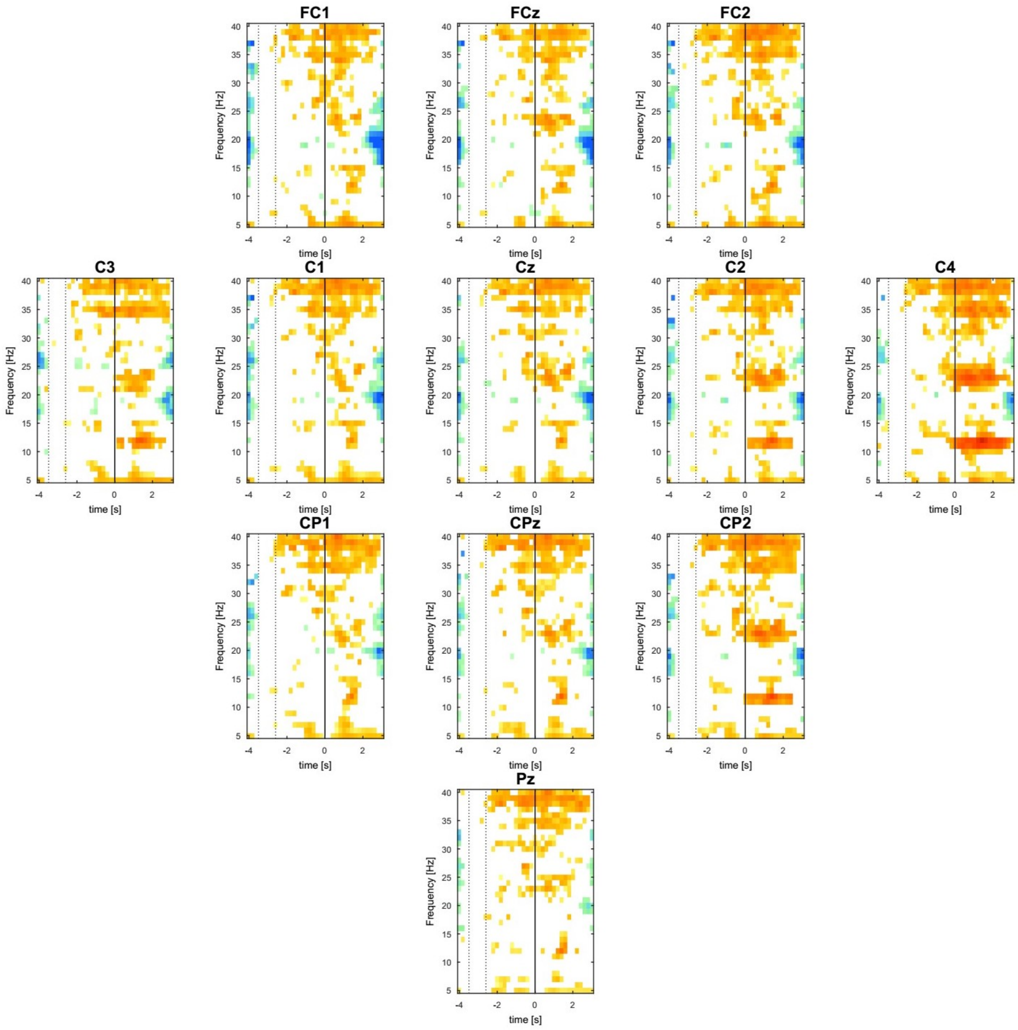

Figure 3.4: ERD/S map hand. t=0: cue onset. reference interval: t=-3.5 s to t=-2.6 s. Significance level: α=0.05

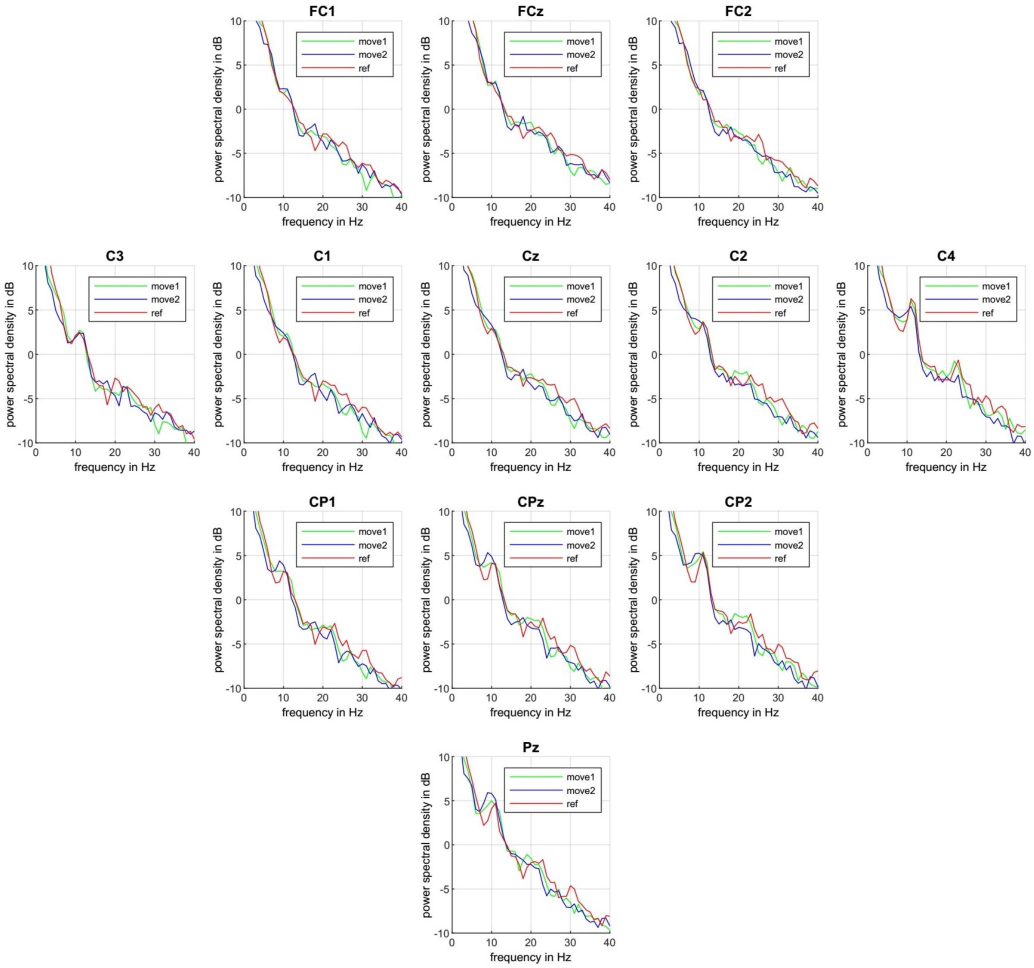

Figure 3.5: Power spectrum foot. move1: interval from t=0.3 s to t=1.2 s. move2: interval from t=1.2 s to t=2.1 s. ref: interval from t=-3.5 s to t=-2.6 s. All time points relative to cue onset.

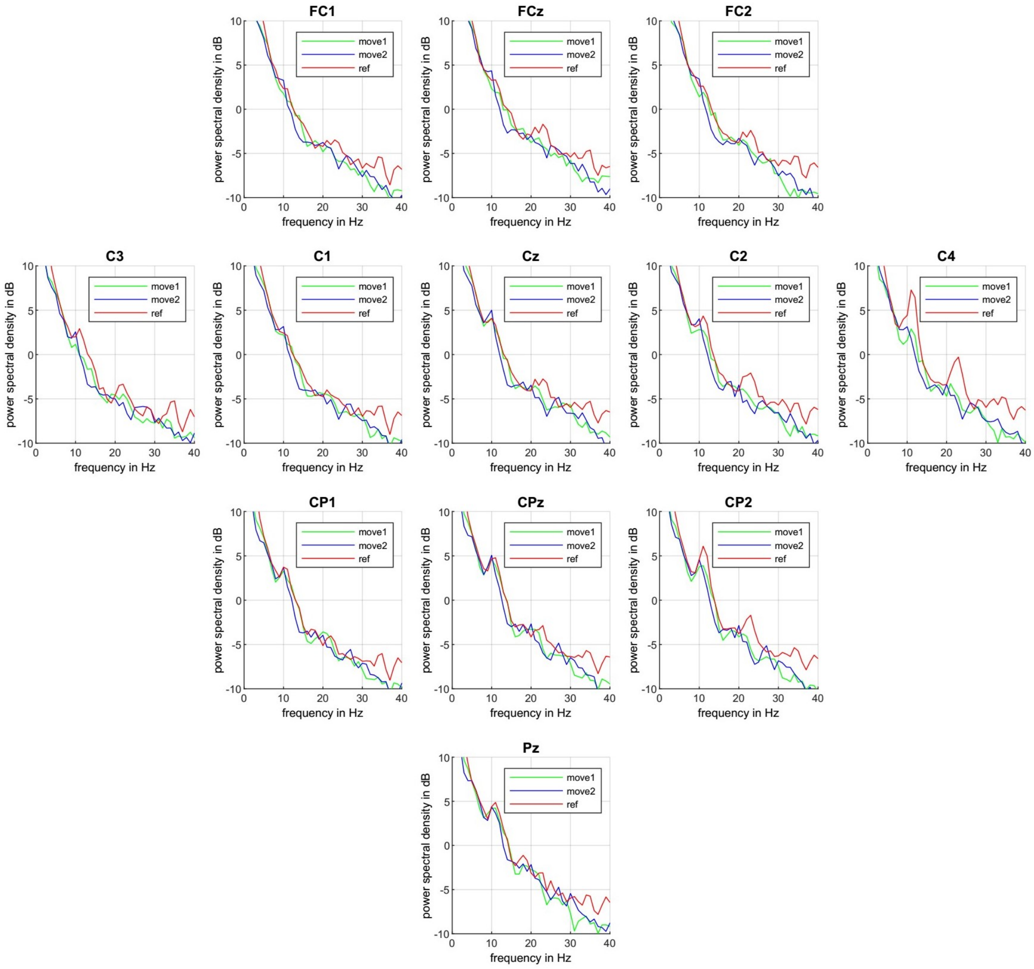

Figure 3.6: Power spectrum hand. move1: interval from t=0.3 s to t=1.2 s. move2: interval from t=1.2 s to t=2.1 s. ref: interval from t=-3.5 s to t=-2.6 s. All time points relative to cue onset.

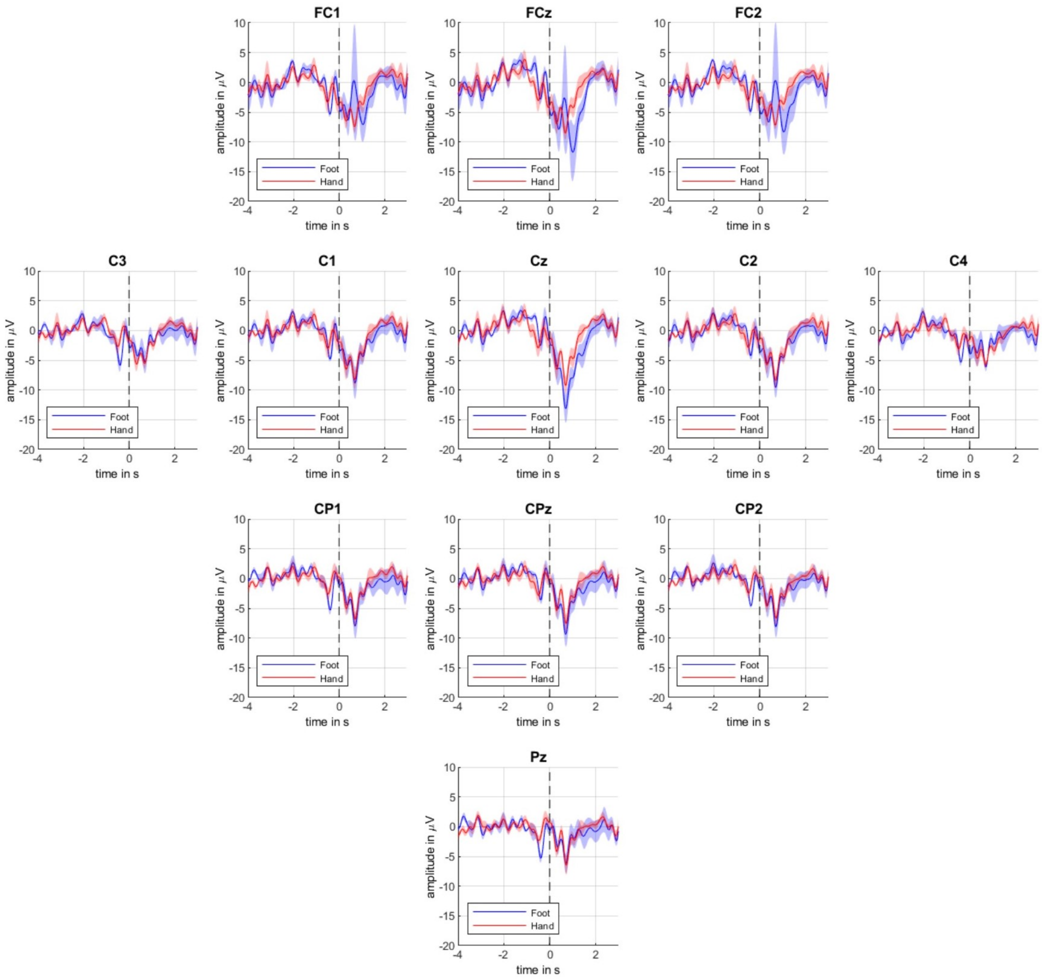

Figure 3.7: Grand average over all subjects: MRCPs of foot and hand movement. t=0: cue onset. Color shaded areas show the standard error of the mean.

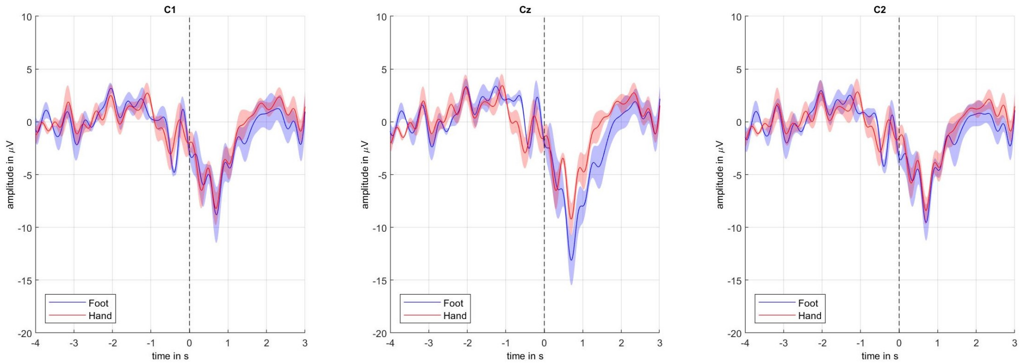

Figure 3.8: Grand average over all subjects: MRCP foot and hand: Close-up. t=0 describes cue onset. Color shaded areas show the standard error of the mean.

4 Discussion and conclusion

One main aspect of this study was to get in touch with the whole measurement setup and to test the created paradigm. Overall, interpretable results could not be obtained in every subject. The failure of the first healthy volunteers was most likely related to insufficient practice of mounting an EEG cap correctly which improved with increasing number of volunteers. Thus the last measurements of study participants worked out fine and lead to good results. The outcomes of one subject are shown in the previous chapter (Figures 3.1 to 3.6). In order to also represent an overview of all participants a grand average over the means of all subjects is shown in figure 3.7.

4.1 MRCP

As already mentioned before, the MRCP is characterized by an increasing negativity of the EEG amplitude [8][11]. This could be seen clearly for foot and hand movement execution after the cue onset (Figure 3.1). The maximum negative shift of the MRCP was found above the central motor cortex

(Cz). Compared to foot movement, the MRCP evoked by hand movement was slightly weaker (Figure 3.1), which is in line with the findings of Luft *et al* and Thomschewski *et al* [14][15]. Since the further aim of the subsequent study is to perform online classification between hand and foot movement, a distinction between the two is necessary and desired.
In the grand average over more subjects the MRCP also could be detected (Figure 3.7). The high artifacts in the frontal row comes from the results of subject S06, which were affected by strong artifacts. Nevertheless, it was selected for the grand average, as the central area displays acceptable results.

4.2 ERD/S Maps

The ERD is related to activated neural structures, whereas ERS occurs usually afterwards and comes with a deactivation of these structures [16]. For movement execution, these processes mainly occur in the μ (7.5 - 12.5 Hz) and β (15 - 30 Hz) [17] frequency bands. After the movement-related power decrease, this effect recovers very quickly, which results in a β-rebound of the β-frequency band through ERS (blue/green area) [16]. For the presented subject, this process could be observed most clearly for hand movements above the central frontal area (Figure 3.4). The results of foot movements were not that clear.

4.3 Power Spectra

The same effect of power decrease in the beta frequency band could be observed in the power spectra (Figures 3.5 and 3.6). The movement interval was split into two parts, because of the influence of different window sizes on the transformation to frequency domain. Therefore the reference and movement window had to have the same size. Thereby, it could be detected whether the movement was executed in the first or second half of movement interval.

This shift of power in the β-frequency band between movement and reference interval could be seen in the central area. For outer electrodes no significant difference between those could be recognized. In the parietal area, α-waves (8 - 12 Hz) [17] were clearly identifiable. The source of those oscillations is the occipital brain lobe.

4.4 Conclusion

It was difficult to find a subject for which all plots displayed acceptable results. However, the most important and desired result is a MRCP, because these results will be used for further studies. The grand average over all means was not very significant. Especially the central area, where the signal is expected to be the strongest, shows some artifacts. This could be related to a small number of subjects with high outliers, which had high impact on the overall result. In addition, it could also be observed that foot movements were stronger affected by artifacts than hand movements. A possible explanation would be that in consequence of the sitting position, it was more difficult to keep the rest of the body still during foot movement compared to hand movement.

Nevertheless, considering individual subjects, the paradigm seems to be suitable for evoking a significant signal, which can be used for further measurements on MCS patients and potentially be used for online classification later on. However, there are certain limitations, as the MRCPs appeared to be not highly reliable for every subject. If the distinction between attempted hand foot movement does not work as expected in further research, only the comparison of attempted and no movement would present a possible approach.

4.5 Outlook

For further measurements on MCS patients several things have to be considered. First of all, the time of potential movement execution needs to be extended as the reaction of people in a MCS takes more time than the reaction of healthy subjects. Furthermore, the trial count per run needs to be decreased distinctly, since MCS patients are not able to concentrate that long and the attempted movements require a lot of effort. To still be able to obtain enough trials the number of runs can be increased instead.

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