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Analysis of motor-related cortical potentials, preparing steps for usage on people in minimal conscious state

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Abstract - English

Brain-Computer-Interfaces (BCIs) have the very high potential to be implemented in almost every purpose for neural rehabilitation and neuroprosthesis. Latest research has proven, that people with neural disorders can use BCIs to restore their lost functions. People in the so-called minimal conscious state (MCS) are not able to communicate in an adequate way with their environment, there is also a lack of investigations about using a BCI on patients in MCS. There is the possibility to find out, if there the is electric activity inside the brain which can be useful to restore parts of the communication system. This thesis is about providing a complete analysis about recorded data from a non-invasive EEG. This analysis consists of the calculated overall average, ERD/ERS-Maps and the power spectrum. The results of all recordings raised the need for a uniform instruction, a clear reference window with no brain activity before each execution. An additional improvement can also be to raise the number of trials patient-dependent and not holding to a certain number of trials.

Zusammenfassung

Brain-Computer-Interfaces (BCIs) haben großes Potenzial, in fast allen Bereichen der neuronalen Rehabilitation und Neuroprothetik eingesetzt zu werden. Menschen im sogenannten minimalbewussten Zustand sind nicht in der Lage, in angemessener Weise mit ihrer Umgebung zu kommunizieren. Es besteht die Möglichkeit herauszufinden, ob elektrische Aktivität des Gehirn genutzt werden kann, um Teile des Kommunikationssystems wiederherzustellen. Neuere Forschungsergebnisse haben gezeigt, dass motorbezogene kortikale Potenziale (MRCPs) dazu in der Lage sein könnten. Um den Einsatz von MRCPs im Rahmen der Wiederherstellung von Kommunikationswegen zu validieren, müssen die durch das nicht-invasive EEG erfassten Daten analysiert werden. An gesunden Menschen wurde eine Analyse nach unterschiedlichen Kriterien aufgebaut, um unbekannte Signale zu charakterisieren. Diese Arbeit bezieht sich auf die erste von vier Teilen, dem Entwurf dieses Analysealgorithmus. Aufgrund des unklaren Feedbacks der wurden auditorische Hinweise verwendet, um die versuchte Bewegung auszulösen. Von den zentralen neun Elektroden wurden Mittelwert, ERD/ERS-Maps und eine Frequenzanalyse zur Charakterisierung berechnet und zeigten einige notwendige Spezifikationen auf. Ein aufgenommene Anleitung vor Beginn des Paradigmas ist notwendig, zusätzlich sollten temporale Elektroden in die Auswertung miteinbezogen werden. Ein zeitliches Referenzfenster vor Ausführung des Tasks könnte eine deutliche Verbesserung der Resultate bringen und gleichzeitig sollten so viele Wiederholungen wie der Patient zulässt erreicht werden.

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1 Introduction

1.1 Aim of the thesis

The aim of this thesis is providing an analysis for a future BCI for patients in MCS. This BCI should be able to restore the communication path between patients in MCS and their environment via a motor attemption task, based on recent findings of [5] and [10]. Suffering from major brain damage, these patients are still alive, but there is feedback from very rare to none. The first step in building this BCI is to create a set of validation data with the corresponding data analysis which is capable to display certain properties of the recordings, which can find further usage for classification.

1.2 Motivation

The current state of BCI primarly focusses onto working with patients, were feedback is possible [17], [12] and sometimes mandatory for the function of the BCI itself. The advantage of an EEG-based BCI is, that there are no special requirements for the measurement itself, the system is applicable with every human being. Moreover, the electrodes are mounted easily and there is no need for surgery. The ongoing research processes of developing EEG systems with higher signal quality which the patient can wear in the daily use. Therefore, the main motivation in doing this whole project comes from the lack of investigations concerning in the development of using non-invasive BCI systems on patients in MCS. The effects of restoring a communication path of patients remaining in this state can be revolutionary for their medical treatment, the personal life quality and future medical research in MCS.

1.3 Special requirements

As no feedback has to be expected, this has to be considered when designing the paradigm and taking the data recordings. In this thesis, the participants are able to give feedback, but there has to be the option to design the paradigm in an expendable way, so that the principle form stays consistent, but the cues and the routine of every trial are adjustable. This is one main reason trying to design the paradigm very simple. Also, when observing the performance of the participants, one can see the actual movement of the participant, this will not be possible when working with MCS patients. The last point not to forget is a consistent instruction to have uniform conditions for every person, doing the paradigms.

1.4 Recording system

There are many different options to record brain activity, starting from near-infrared spectoscopy (NIRS), magnet electroencephalography (MEG) and the most common one, the electroencephalogram (EEG). NIRS has aleady been used for motor imagery [9], there is also MEG-based BCI [11]. An MEG is not suitable for MCS patients due the availability of the hardware and the necessity of the patient staying in bed. The EEG offers 2 different options: an invasive method, which requires surgery, and non-invasive systems. A non-invasive EEG has approved in the past in many studies about BCIs and recordings about attempted movements [12], [5]. This is resulting on only one option for the recording system: a non-invasive EEG.

1.5 Hypothesis

Looking at current research in Brain-Computer-Interfaces (BCI) and neuro-rehabilitation, currently there are many results in integrating BCIs in the rehabilitation process of stroke patients, especially when they suffered from somatosensory or motor control damage. The basic idea is, when the neural system gets damaged, using a BCI to derive the missing neural function from the residual neural capacities. Motor imagery already delivered serious results when working with stroke patients [7],[1], but the question now is: Can we use a BCI somehow to derive an control signal which enables communication paths between patients in MCS and their environment? The basic idea is to use an non-invasive EEG, recording the brain activity, and a PC to extract features about imagined movement of limbs. These features can be used further for feeding a classifier, if the gathered feature have usable significance and futhermore distinguish different answer options for the patient, e.g. ”yes” or ”no” answers. The first step for this achievement is to set up an analysis algorithm which characterizes the recorded data. This should provide the necessary information about further usage.

2 Methods

2.1 Paradigm

EEG-recordings have a high noise content, coming from the brain activity, technical and biological artefacts and maybe bad electrode mounting. The main goal in designing a good paradigm is adapting the required task (movement, reaction task, focussing on tones,...) that the participant delivers the demanded signal while reducing biological artefacts. There is the question, which kind of cues are given to the participant in order to use it on MCS-patients later on. Also the timing and the numbers of trials per run and per class are mandatory to give low-noise results while minimizing the cognitive load.

2.1.1 Task

Current research [16] shows, that a very efficient way to use motor-related cortical potentials (MRCP) is to give tasks involving hand or foot movement. It is very easy, to give advisory moving these limbs and most importantly, the amplitudes of these MRCPs are raising up about 2-10 μV, a relatively high value. The verbally given introduction included a very precise description, how the movements shall be executed. In general, the participant sits comfortably in front of a desk. For the hand movement, both hands must rest on the desk in a way, the participant does not have the need to move for about five minutes and a fist can be easily made. When hearing the order to move, both hands should be closed to tight fists followed by the immediate release. The feet movement had to be a brief dorsi-flexion of both feet. While sitting, this movement should be performed in a way, that the rest of the body hardly moves to avoid additional noise sources (additional muscle activity, electrode sliding). Both movements were performed relaxed, but in one single action, so that the closing-releasing-movement and the dorsi-flexion-streching were single movements, this leads to one single MRCP. If there is a break between action setting and resetting, the result will be an overlay result of two MRCPs.

2.1.2 Noise reduction

The EEG has an amplitude between 1 μV and 20 μV, biological artefacts can bring in noise up to several mV. Eye rolling, swallowing or eye blinking result in low noise in the range of several μV, but are still too high. The electromyogram (EMG) of the neck muscles result in a very high noise level, that high we can't even see the actual EEG any more in the scaling of μV. Suppressing these biological artefacts, the acting participant has to receive clear instructions about possible noise sources and is a main influence factor of the actual result. To reduce the noise level in general, the movement task is repeated many times. In general, a high number of repetitions is useful as showed by [14], but in this task, there must be thought about the cognitive load for the MCS patients. Instead of having a high number of trials per run and a low number of runs, only 20 trials per class were set and in order to react on the cognitive load for the participant, and later on, the MCS patient, just the highest of number of runs possible was set. For the participants, four runs per paradigm and per person were done to get 160 trials per person.

2.1.3 Cues

Former MRCP tasks were performed with visual cues, but now it has to be considered that later on, the patients might not be able to focus on a screen. Auditory cues have the advantage, that the participant does not have to focus explicitly on a screen or a cross, he just has to be arouse of what he is hearing. Auditory cues were already used with patients in MCS by [2]. The cue for the hand movement was a high sinus-wave generated tone and for the foot movement a low sinus-wave generated tone. Ending the trial was indicated by a double-tone in a frequency between the high and the low tone. The participants had to run through a test trial, in order to get to know these different frequencies. Also to avoid accommodation to the order of either hand or foot is coming next, the cues were pseudo-randomised. There is just one aspect to be considered, that the auditory signals can result in evoked potentials (EPs) which add up to the MRCPs and give us noisy results again.

2.1.4 Timing

The timing of every event was orientated by previous investigations concerning similar tasks, such as [16], [3] and [4] did. The paradigm contained

EEG system	mounting	noise	signal gain	costs
water based	fast	low	good	very high
electrolyte gel based	medium	medium	good	high
dry	fastest	high	bad	low
watergel based	medium	low	good	very high
passive electrodes	slow	medium	very good	medium

Table 2.1: Short overview of non-invasive EEG systems

a little timespan to allow every participant doing actions like eye-rolling, swallowing and eye-blinking. If the participant does it during the trial, the trial is either lost due to the artefact-filtering or it heightens the standard deviation, making the results fuzzy. The participants were precisely introduced to the paradigm and the possible artefacts they could possibly bring into the measurement, with the explicit order to reduce sources for biological artefacts as much as possible.
The specific timing of the single cues were: Three seconds start-off (participants started the task by themselves), high/low sound for hand/foot-movement (2 classes), after three seconds a double-sound for ending the trial. Afterwards there were two seconds break. This routine was repeated 20 times per class, so all in all 40 times with a pseudo-randomisation to avoid accommodation. For every participant, four runs were recorded.

2.1.5 Electrode set-up

We chose active electrolyte gel based electrodes due to the very suitable properties as shown in table 2.1. In the first place, we wanted to reduce the time required for the mounting process. This avoided unnecessary cognitive load for the participants.
The main section of interest covers the hand/foot sections of the motor homunculus, which is located in the central area of the head. The homunculus provides the regions for hand and foot activity, so the mainly selected sections for electrode positioning are around Cz. As we do not know, how the auditory cortex reacts to the cues, the decision was made to also use electrodes in the temporal area, just to quantitatively participate whether there is activity or not. The hardware was orientated in a similar setup as seen in [4] and [8]. For the recordings active electrodes 'g.LADYbird' (g.tec) in combination with a biosignal amplifier 'g.USBamp' (g.tec) were used to record the datasets.

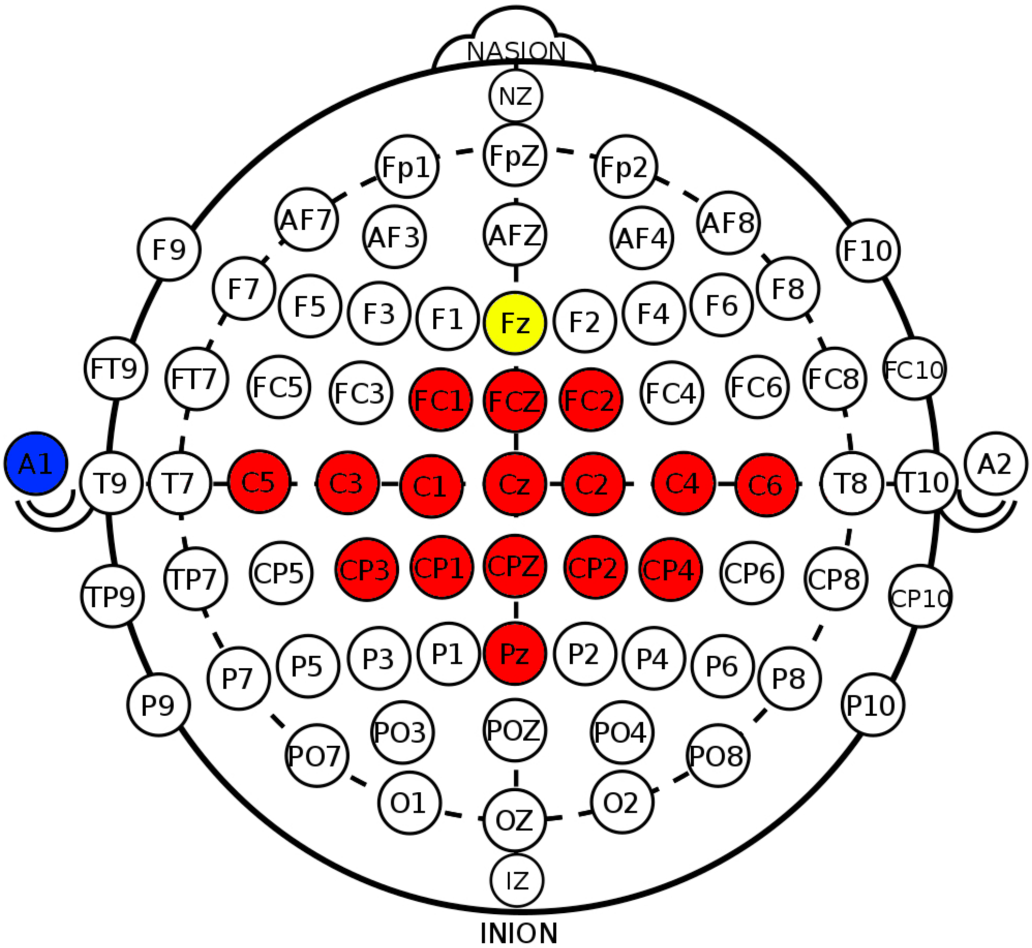

Figure 2.1: The setup of the used active g.LADYbird (g.tec) electrodes around the primary motor cortex. The used ground electrode is located at the 'Fz'-position and the reference was clipped onto the left ear, 'A2'.

The electrodes were finally selected, in order to achieve the points above: frontal-central, central and central parietal areas were each covered by the whole central area around 'Cz', including its all its neighbours. Also 'FC3'/'FC4' , 'C3'/'C4' and 'C5'/'C6' were included, the central also contained the temporal electrodes for the auditory signal. Finally, 'Pz1' was also added, making the central line complete. The ground electrode was placed on the forehead 'Fz' and there was also a reference electrode added on the left ear 'A2'. Detailed electrode positioning can be seen in figure 2.1

2.1.6 Participant introduction

13 participants, aged from 21 to 27 took part. The person wearing the EEG-cap can influence the results very strongly by avoiding biological artefacts, focussing on the given task and performing the movements exactly as introduced. In this project, it will not be possible to get many trials per run and it also will not be possible to record many trials. The introduction was performed equally to every participant giving the possibility for every participant to start a single run on his own, whenever he was ready. A test run was primarily done to introduce the frequencies, the volunteer is about to hear. All of the persons were sitting in the EEG measurement box which is damped to sound, shielded from electromagnetic fields and gets closed during every recording. During the measurement, there is no possibility to correct anything, just between the single runs which can result in a whole run performed wrongly. During the runs, every participant was observed if he performs correctly and if there rises up any problem.

2.1.7 Signal processing

For every hand/foot movement, the overall average, an ERD/ERS Map and the total power spectrum were calculated. These characteristics have been used in multiple research projects concerning motor tasks, motor imagery and MCS. The time-domain MRCP characteristics have been described by [16], [21] and [3]. Further frequency-domained properties are shown by [12], [15] concerning the power spectrum. Time-Frequency domained ERD/ERS maps have been used as shown in [13], their advantage and usage as well as their power to bring significance has been described in the works of [10], [6], two times by [18], [20] and furthermore [8]. Almost all of them use ERD/ERS maps for indicating motor action in the primary motor cortex in the frequency range of the μ-rhythm and beta rebound [19] with significant results in decoding properties and features out of the ERD/ERS maps. The calculations of this analysis were done with MATLAB v2018a, using the external libary "eeglab". To show details out of the diagrams, the central three sections of all electrodes are shown. The full recording data can be found in the appendix (showing 16 recording electrodes). The electrodes being presented and further discussed are 'FC1','FCz','FC2','C1','Cz','C2','PC1','PCz','PC2'.

Filtering & Artefact detection

The verbal introduction leads to better results in common, but still there are some outliers left. Most of the technical artefacts can be compensated by a correct setting of filters and electrode mounting in combination with the instructions. The biological artefacts cannot all be removed by filters, after the data recording we have to use a software solution to detect these artefacts and in the final signal processing, these artefact must not be considered.
The following adjustments for filtering and artefact detection are inspired by the work of [21]. The g.usbamp biosignal amplifier can be run with several filter settings, as the raw EEG is sampled with 256 samples per second, the highest frequency detectable can be, due to the Nyquist criterium, 128 Hz. MRCPs are in range of 0.3 to 3 Hz [21], but for further signal processing a maximum of samples makes sense. Two filters were finally used, an 8th order chebyshev filter, for bandpass-filtering between 0.01Hz and 100Hz, and a notch filter to get rid of the 50Hz artefacts.

Analysis filters

Different analysis aspects require different filter settings. In the analysis section, the average calculation, an ERDS-Map and a frequency analysis was done per participant. Therefore, the bandpass filtering was done with different settings. For all analysis sections, we applied a common average reference filter, as already [21] did.

- The overall average calculation gives a closer look on the actual MRCP, as we already know from [21], the interesting frequency bandwidth is 0.3Hz to 3Hz.
- Taking a look at the overall activity, the ERDS-Map gives a closer look, in which freqency band one can see synchronisation or desynchronisation. As we are dealing with motor actions, we expect frequencies in the alpha-bandwidth, more detailed in the low μ-bandwidth from 8Hz to 10Hz. Also the beta-rebound [19] has a weighted role for the general activity, located at about 20Hz to 30Hz. This leads to a bandfilter setting of 1Hz to 40Hz. The final ERD/ERS Maps were generated by a provided MATLAB libary from the Institute of Neural Engineering.
- The frequency analysis will show the difference between action onset and movement performance, taking a closer look should result in a difference in a similar manner as one can observe in the ERDS-Maps. As we want to look at the whole spectrum, a bandwidth of 0.2Hz to 50Hz includes all the aspects possible to look at. The calculation of

the spectrum was done with the MATLAB libary 'eeglab' by using the 'spectopo' command.

Artefact detection

After the preprocessing, the biological artefacts must be removed. Different arithmetical and statistical aspects can lead to a positive outlier rejection, criteria are for example the standard deviation, maximal amplitudes, probabilities for the trial being artefact free. Also for the detection itself, a bandpass filter from 0.3Hz to 50Hz is used. For these purposes, the already mentioned MATLAB libary from the Insitute of Neural Engineering (reducedOutlierRejection) also provided a command ('PerformOutlierRejection') for detecting artefacts.

3 Results

3.1 Recordings with expected MRCP characteristics

The following diagrams and figures do have significant results, however the standard deviation is relatively high. This can be the result of relatively high noise level or it can be reasoned, that all trials have similar properties within $\mu \pm 3std$, which means about 99% of all trials are considered. If these trials have very different properties within this tolerance span, the results get fuzzy on the one hand, if more trials are rejected, the MRCP disappears in the final calculation and gets overlapped by either the noise sources or the evoked potential, if there is one.

3.1.1 Foot movement

In figure 3.1 can be seen, most electrode recordings except 'C2' and 'Cz', show activity related to the cue: right before the vertical line, a slight onset is visible, the potential rises up a little bit. At the movement onset (t=0.2s), the potential drops down and rises up after about one second, the foot movement results in an amplitude of about 5-10 μV. After this movement, the potential returns to the approximate level of zero. 'C2' does not have a clear sign of this described graph. The row 'CPx' does seem to bee the symmetric equivalent to the 'FCx'-row, this might be a result of the CAR. This is later investigated in the grand average analysis of the last few participants. Figure 3.2 shows the brain acticity on each electrode over the whole timespan of the overall average of trials. The maps were calculated by 40 overlapping intervalls of 2Hz. Blue indicates neuronal synchronisation, orange/red directs to neuronal de-synchronisation. The reference intervall for no activity is defined from -1s to -0.2s (start of auditory cue) and is graphically found by the mostly white colored space. Features are on the one hand, the high de-synchronisation in the frequency band of about 8Hz to 10Hz at t=0.3s to t=1s and the following beta-rebound [19] in a bandwidth of about 20Hz at t=2s to t=3s. The fronto-central electrodes show the μ-rhythm very strongly, as well as the beta-rebound. The central electrodes show activity at a similar timespan, but no clear beta-rebound.The centro-parietal electrodes also show activity beneath 10Hz, but in a very wide bandwidth. Also the beta-rebound is visible. The expected power spectrum is shown in figure 3.3, indicating a continuously falling red curve (intervall before movement) as there is no special activity before the cue. A power high for the green curve (intervall after movement) in the bandwidth of 8Hz-10Hz is definitely visible in all electrodes except 'C2'.

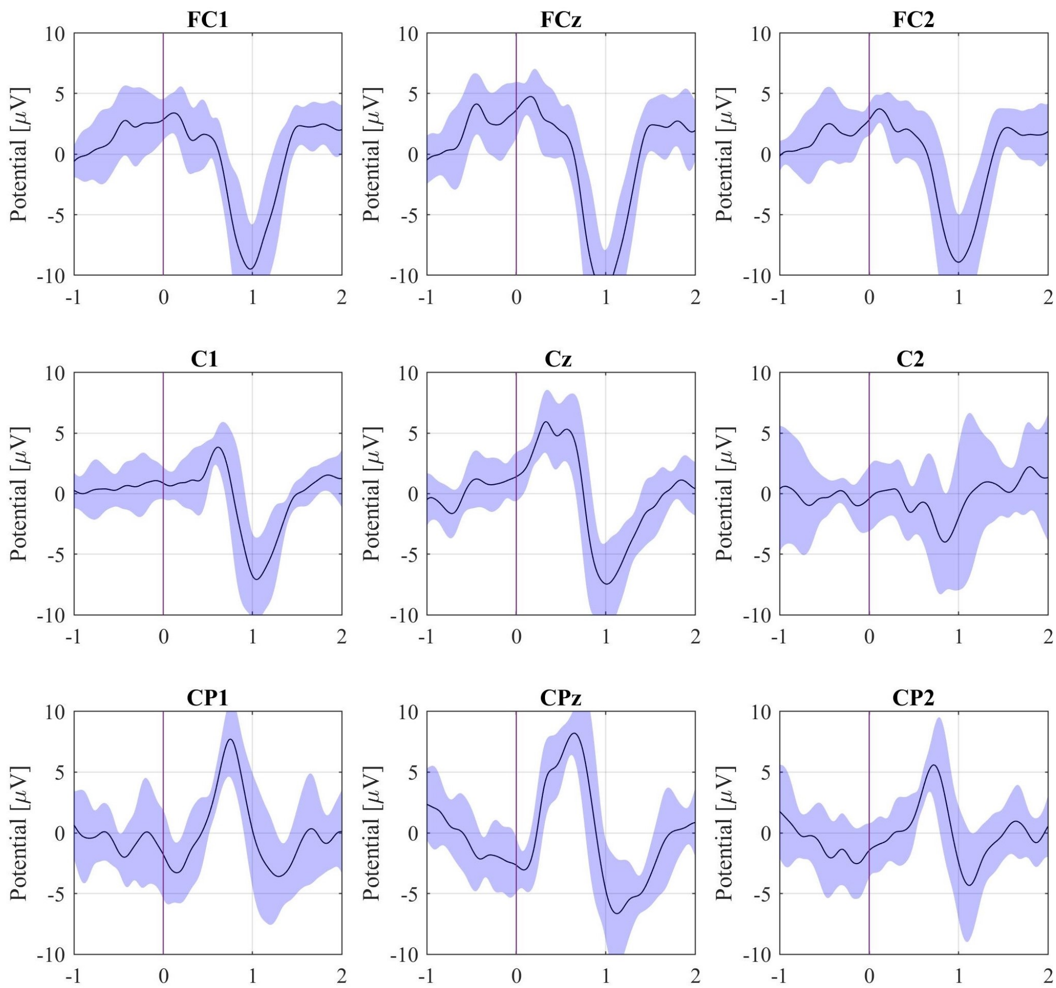

Figure 3.1: Overall average of foot movement showing activity to auditory cue.

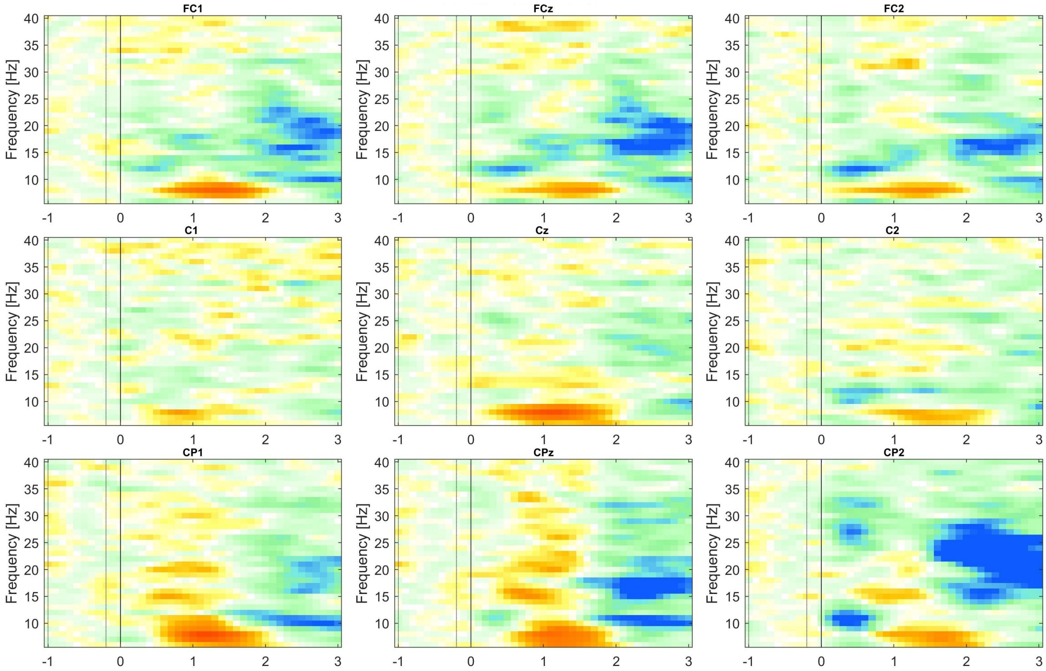

Figure 3.2: ERD/ERS Map of foot movement showing de-synchronisation briefly after the movement onset and synchronisation after the attempted movement

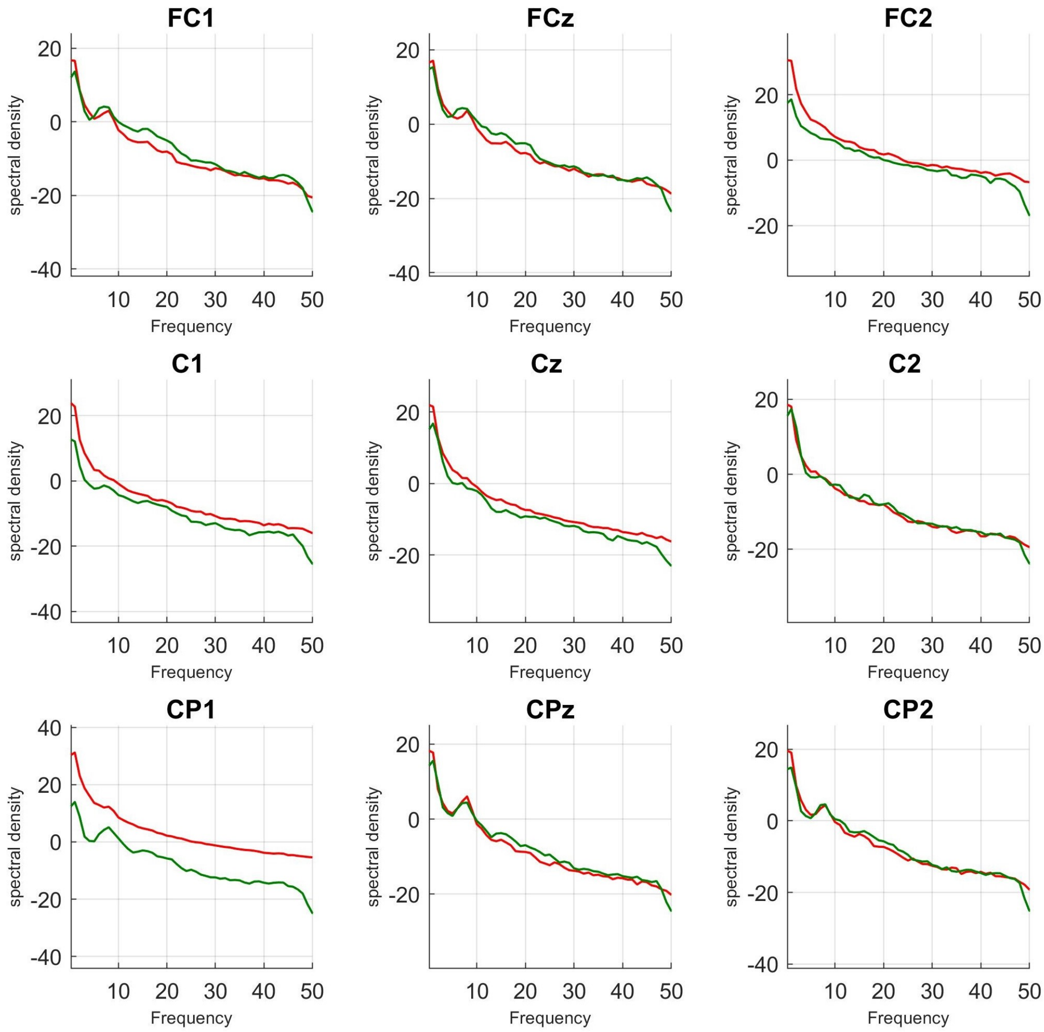

Figure 3.3: Power spectrum of foot movement comparing a timespan from [-1s -0.2s] and [0s 1.8s]. A slight difference at approximately 8Hz-12Hz is visible.

3.1.2 Hand movement

In general, one can say that hand movement result in lower amplitudes for the MRCP than foot movement, a maximum of 6 μV is observed. Figure 3.1 shows very similar properties as already discussed in the results for good quality foot movement, showing that also hand inducted MRCPs have similar properties, e.g. 0.3Hz-3Hz bandwidth and an amplitude of about 5 μV. The centro-parietal line of electrodes do not have clear features. Also the horziontal symmetry of the 'FCx'/'PCx'-rows is observable (also as seen in figure 3.1). There is a small hint in 'CP3' to an MRCP-similar graph, but with a very low amplitude and high standard deviation in relation to the amplitude itself. The ERD/ERS-analysis for the hand movement, displayed in figure 3.5 also showed general activity during the movement inteval in the bandwith of beneath 10Hz. The centro-parietal as well as the fronto-central electrodes also show a beta-rebound. In almost all electrodes, the higher frequency bandwidths show neuronal desynchronisation. The frequency-domain analysis in figure 3.6 displays a quite flat decreasing curve with raising frequency domain in the red graph (time intervall right before the cue). The green graph displays a peak in the frequency intervall of 8Hz-10Hz at a later time intervall (attempted movement).

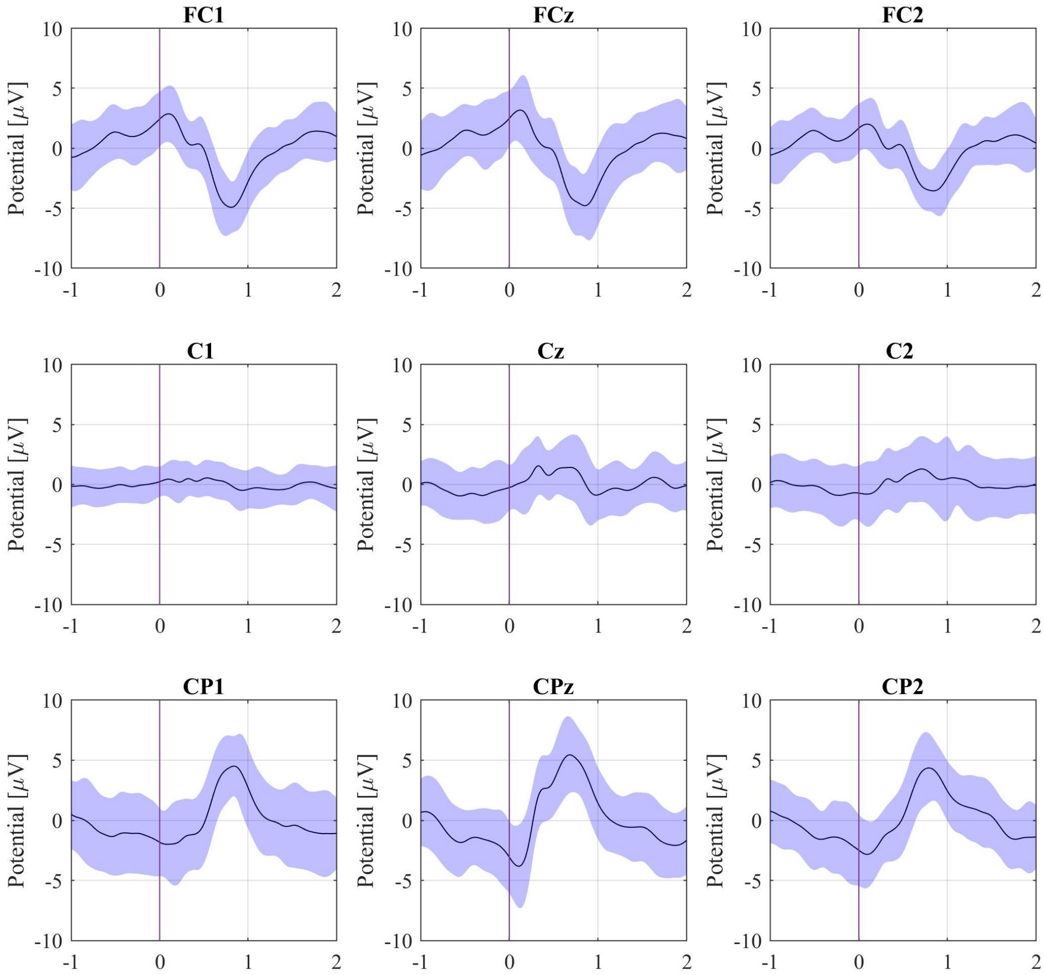

Figure 3.4: Overall average of hand movement showing activity to auditory cue.

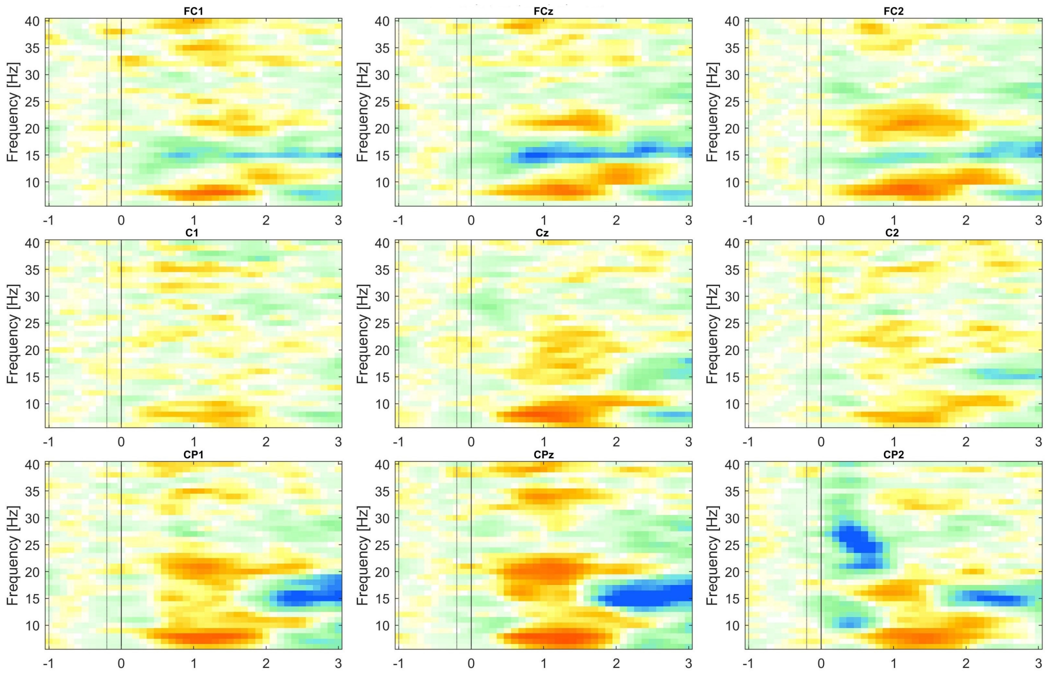

Figure 3.5: ERD/ERS Map of hand movement showing de-synchronisation briefly after the movement onset and synchronisation after the attempted movement

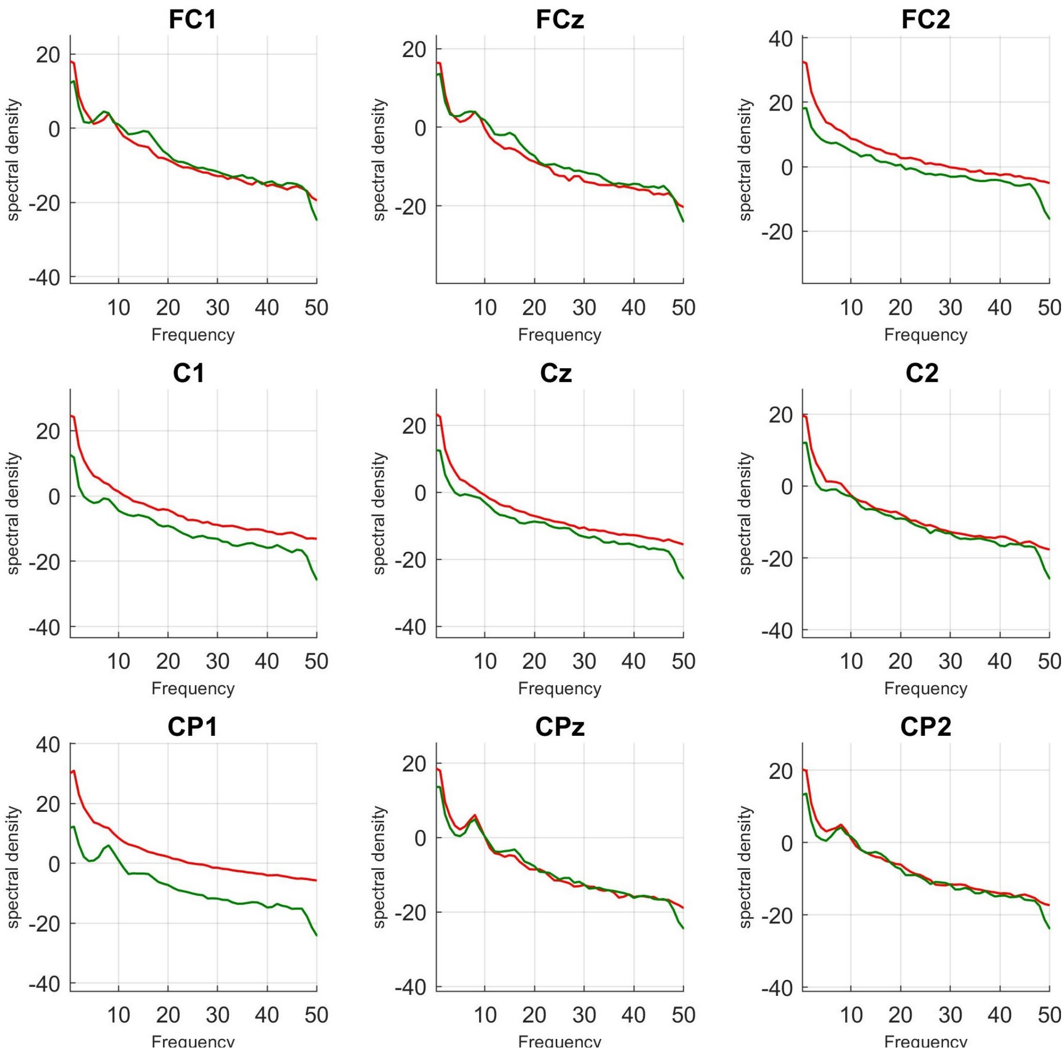

Figure 3.6: Power spectrum of hand movement comparing a timespan from [-1s -0.2s] and [0s 1.8s] - usable data

3.2 Grand Average

The results shown have properties, which can indicate MRCPs activity. Since the first recordings had a bad outcome (electrode mounting, bad introduction, misunderstandings of the paradigm, many artefacts during trials) we calculated the grand average(without CAR) of the last 5 participants, which did have the lowest number of trial rejections. CAR has not been performed, as the signals received a horizontal symmetry and the features were eliminated.

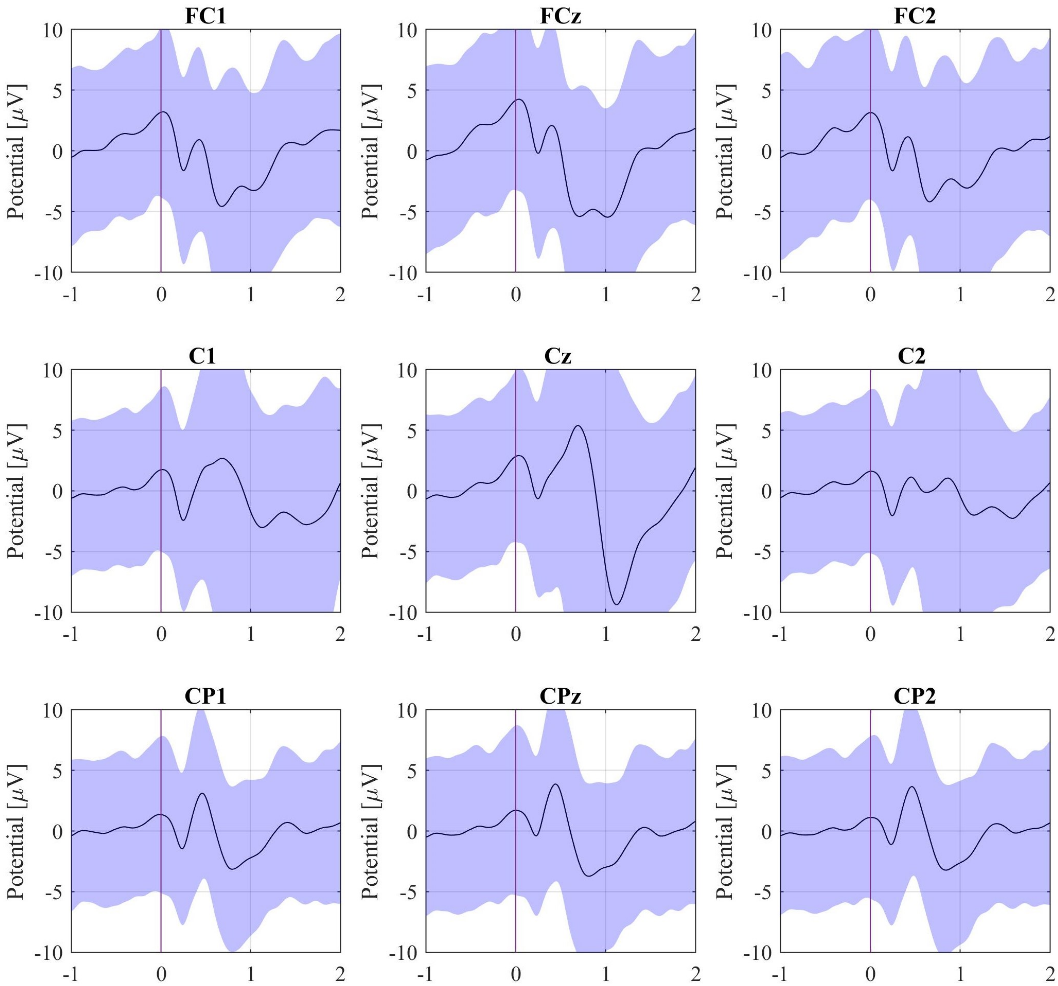

Figure 3.7: Grand average of foot movement - Participants 9-13.

The grand average in figure 3.7 shows the averaged foot movement of the last five participants. Though there is a high standard deviation, it is observable that every electrode has activity referred to the cue. This activity is also symmetric, as both feet were moved. Every electrode has a slight onset, followed by a drop. Some electrodes (e.g. C1) might contain extra features, which interfere with the motor activity.

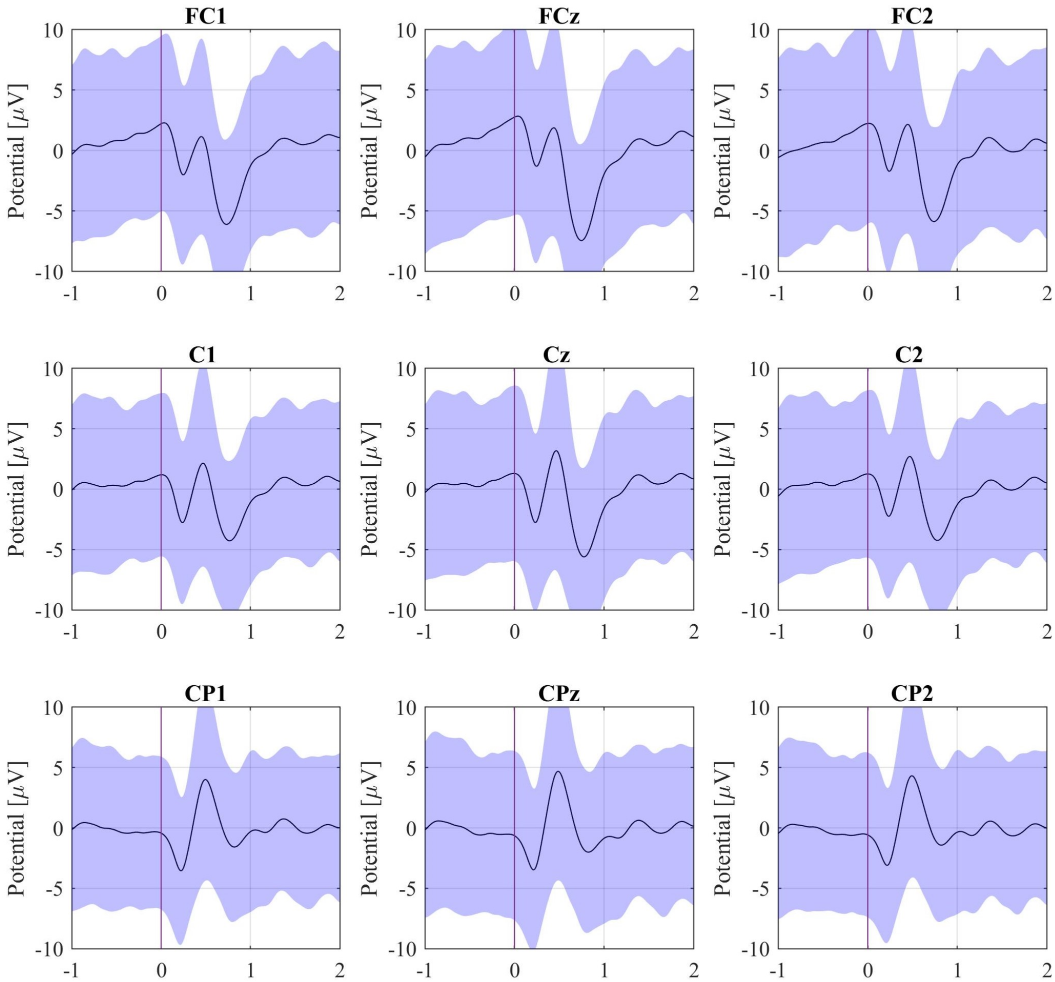

Figure 3.8: Grand average of hand movement - Participants 9-13.

In figure 3.8, the electrodes recorded another feature: the fronto-central row recorded activity, which has first a positive onset followed by a signal drop. All other electrodes do have a similar curve trend, but the amplitudes are not clearly positive, they are oscillating briefly around the zero-level. Comparing the fronto-central row with the centro-parietal line, there also is a kind of horizontal symmetry observable.

4 Evaluation

4.1 Instructions

The instructions for the participants were given in the exact same manner, giving equal conditions to every recording. Still, the participant's interpretation of these orders differed very heavy, especially when it came to the way, how to perform the motor task itself. The test run which was given to get the paradigm to know, eliminated the questions about which tones are coming up and the persons got a feeling for the timing of the paradigm. Sometimes, the participants performed a whole run holding the fist tight or they did not relax their feet after raising it until the trial was ended by the double-tone. This made a whole run being a single artefact source, pushing the standard deviation higher. The suggestion for avoid these misunderstandings would be a recorded instruction and a test run, were the performance of the recorded instruction is observed. The test run should not be considered in the final calculation, except the performance is in a correct manner from the first trial.

4.2 Paradigm

The paradigm was constructed very simple and has a very quick performance time to run through fast, minimizing the cognitive load time. The disadvantage which occurred in the final analysis was that the short runtime hardly allows the acting person to blink, swallow or move the eyes which resulted in the final analysis in many trial rejections and a lot of artefacts. Which such a low final number of trials, this makes the process of feature extraction very hard.
Another and probably the biggest problem is the reference interval for the time-frequency domain ERD/ERS-maps. The paradigm contained a short timespan allowing the participant to blink and briefly move, but the end of this little break was not clearly separated by a cue. The instruction contained the timing of the paradigm, but the break was obviously designed too short.

This resulted in a fuzzy reference for the ERD/ERS-calculation, though there were significant results observable, the reference must not contain activity.
The improvement of the two issues above can be achieved by extending the paradigm: after the trial ending double-tone, there should be a break of 2s-3s allowing the participant to blink, swallow and so forth. The break will be followed by a auditory cue, indicating that the motor execution comes next and the participant should focus on the task. This expands the trial of about three seconds, but provides an activity-free reference interval, more time to prepare and to relax between the trials.
The last point regards the auditory response. In every trial of each class, the cue is given exactly equally which means, if there is an auditory response recorded in the electrodes on the motor cortex, this feature is included in every trial. In a few recordings, features very similar to an evoked potential have been observed. The CAR seems to be a quite good filter for this problem. In the most cases, there is no clear auditory response visible. The feedback of these participants also showed, that sometimes the person focussed more on the auditory cues than on the actual movement. A clear suggestion of improvement cannot be made here, as the thesis does not investigate the auditory response. One possible option could be, to use more electrodes on the temporal cortex to record the local response.

4.3 Qualitiy of measurements

During the analysis of all datasets, the recordings turned out to contain many artefacts. The signal quality in general (noise level, number of artefacts, drifts) was very bad during the first recordings an improved until the last participant. The grand average of the last 5 participants (AC09-AC13) showed better results but still leaves questions open regarding the source of the unexpected features.

4.4 Data analysis

Section 3.1 showed, that the shown properties of the measured EEG data can clearly show, if there is a adequate response to the paradigm from the participant. There are three ways to detect a hidden feature inside a stream of measurement samples. The overall average shows the time-domain response which should be used as control signal (online classification). The better option could be to use attempted foot movement in the first place as the amplitude is definitely higher than at attempted hand movement. The ERD/ERS Maps should be used for offline classification due to the high computing time. The frequency-time domain clearly shows if the activity is referred to motor activity. The calculated power spectrum can be used for offline and online classification. The primary usage should be a validation function, the difference we observed in our calculations is visible but not as clear as the other features we analysed.

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