Measurement and analysis of cortical activity using EEG during upper limb stabilization

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by

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Contents

1 Abstract

This Research Assignment gives an overview about the project i was working on during an internship at the Integrative Neuronal Engineering Research Lab at Marquette University in Milwaukee(USA). The paper includes the basic ideas, as well as the development and execution of an experiment on the cortical representation of voluntary and involuntary upper limb movements during the presence of tendon vibration. Sensorimotor impairments are a common accessory symptom of many neurological diseases lake multiple sclerosis or stroke. In order to find ways of better treatment of those deficits, the processing of sensory information by the brain and its influence on motor control has to be investigated in detail. The experiment that was carried out in order to focus on this problem has six conditions based on the two factors volition of movement and duration of tendon vibration. Information from the brain during the tasks were collected via EEG. The results observed until now show, that tendon vibration severely increases movement related oscillatory effects in the sensorimotor cortex of the brain in cases of voluntary as well as involuntary movements. This leads to the conclusion that stimulation of muscle spindles using tendon vibration, when applied in short time intervals, can affect the activation of motor regions in the brain. This effect was observed to be most prevalent in the alpha frequency band. It was also discovered that tendon vibration, when applied for longer periods of time does not seem to influence band power in the observed frequency range.

2 Introduction

In order to control and perform precise limb movements, the human brain relies on a wide spectrum of sensory feedback. Examples for those can be vision, tactile sense or proprioception. Deficits in proprioception caused by stroke or multiple sclerosis can lead to severe restrictions in walking, precise arm movement and several other tasks. In order to find proper treatment for people affected by those sensory restrictions, it is important to understand in which way the brain uses sensory signals for movement control. Previous studies have shown that artificial sensory stimuli can affect the precise execution of arm movements in both negative and positive ways. Examples for those kinds of stimuli can be electrical impulses or mechanical vibration. Especially mechanical tendon vibration in frequencies around 80 Hz has shown wide effects on proprioception by selectively stimulating Ia-afferents, responsible for proprioception. Electroencephalography (EEG) is a well-established way to examine brain activity during active and passive movements. Changes in the -Frequency band over sensori-

motor areas as well as slow cortical potentials can be associated with motor activity. During the internship at Marquette University, students at the INERL(Integrative Neuronal Engineering Research Lab) were working on ways to examine these effects in several different ways. We hypothesized that tendon vibration, applied during active and passive point to point arm movements leads to significant changes in the human EEG by affecting -band power and slow cortical potentials. Analyzes of EEG signals and hand position data were used to investigate the effects of brief and prolonged tendon vibration on the motor cortex during simple point to point reaching tasks. This report summarizes the the work done at Marquette University and gives insight in some of the results found.

3 Theoretical Background

In this section, the most important theoretical aspects concerning the experiment described in section 4are explained. Thereby the focus is on the basic principles of Electroencephalography, the method used to observe brain activity as well as on the signals it generates and how to interpret them. Also some fundamental aspects of neurology and the effects of tendon vibration are explained.

3.1 Overview of Electroencephalography

The basic method used for the study explained in this paper is electroencephalography (EEG). EEG is the recording of electrical activity over the brain. The method is widely used in clinical application for example for seizure-detection as well as in neurological research.
In the last years, alternative methods to EEG such as FMRI (Functional Magnetic Resonance Imaging) or MEG (Magnetoencephalography) have become more and more important. Even though EEG still outperforms these systems in temporal resolution and handiness. The potential of highly developed signal-processing methods such as Independent Component Analysis also opened new possibilities and fields of application for Electroencephalography. With those methods it is now possible to localize signal sources in the brain and to reject movement artifacts so that it is possible to even record EEG during complex movements or even walking.

3.1.1 Historical Aspects

Despite all modern fields of application, electroencephalography is in fact a very old way of researching brain activity. The first EEG device was built by German

Physician Hans Berger (1873-1941) by trying to find the physical basis of mind. By that time science was aware that the brain was responsive to electrical stimuli, but because of a lack of technology, especially high-gain amplifiers, electrical activity as small as the electroencephalogram could hardly be examined. After a lot of unsuccessful trials with a capillary galvanometer, Berger finally found a signal that can be considered as an EEG, by using a double coil string galvanometer together with a primitive oscilloscope. The crucial difference between this and his former experiments was, that he selected subjects who had suffered from traumatic brain injuries and had lost parts of their scull which allowed Berger to record EEG without the high resistance of bone tissue. After further developing his techniques by using saline electrodes, Berger was finally able to record EEG-signals from healthy subjects.[1] Berger was also able to destinguish between waves of higher frequency and low amplitude and lower frequency and higher amplitude which can be considered as α and β waves (Section 3.2.1). Even though being rather revolutionary, Bergers findings got no recognition until 1934. After being accepted by the science community EEG-recording techniques were further improved by the development of multi-channel EEGs and better amplifiers.

3.1.2 Functional Principle

Unlike other methods like magnetoencephalography (MEG) or Magnetic Resonance Imaging (MRI), the function of EEG-devices is rather simple and straight. It records electrical activity over the brain caused by neurons changing their electrical potential in order to exchange information. This signal is further explained in sections 3.2 and 3.2.1. The first part of the chain that processes the signals is the electrodes which will be focused in section 3.1.3. Their main purpose is to reduce resistance between the skin and the device to a minimum. Some modern devices have active electrodes, which also do a first step of amplification. In order to make the EEG visible, it has to be amplified. Therefore the principle of a differential amplifier is used: Two signals, one from the electrode and one from a reference get subtracted and their difference is amplified. This leads to good suppression of potential shifts affecting both electrodes similar. For digital EEG-systems, the signal then has to be sampled and quantified. The minimum Sampling frequency which is twice the highest frequency of the EEG signal is 200Hz. Nevertheless sampling rates up to 2000Hz are used in modern systems. After being sampled the signal is quantified with a resolution of usually 16bit. After amplifying and digitalizing the signal can be examined in different ways. The most traditional and simplest way is looking at the EEG in time domain. Therefore the different channels are usually drawn as lines below each other. Figure 1

shows an EEG recording in time domain. Even though experienced physicians can use the unfiltered signal in time domain to diagnose, usually specific frequency bands are filtered out and the EEG is examined in frequency domain.

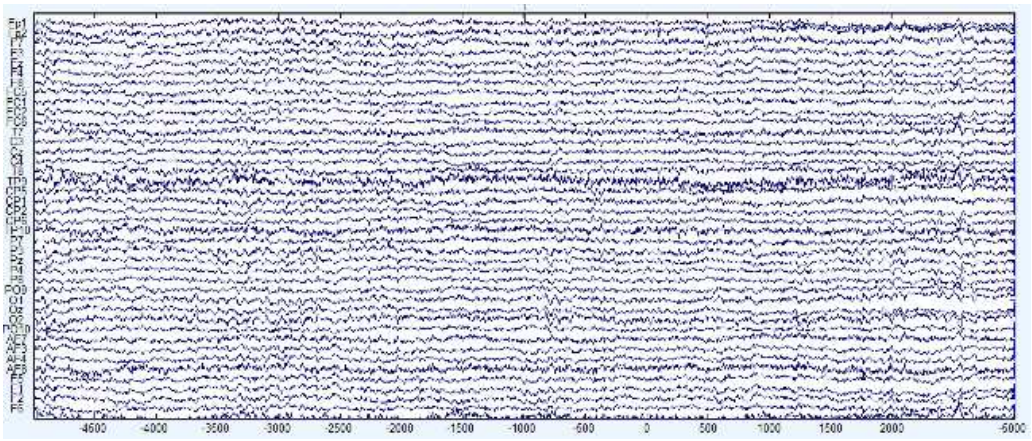

Figure 1: 5 seconds of EEG signal in time domain. (30 of 64 electrodes)

Due to the very low amplitude of the signals, EEG recordings are very sensitive to a high number factors causing different artifacts. The artifacts can be separated into artifacts caused by the subjects body and external artifacts. The most known external artifact which is very easy to remove is electrical noise especially from the electric installation. The typical 50Hz(Europe) or 60Hz(USA) can be rejected using a band-stop filter.[2] Other artifacts like electrical noise, impedance shifts or even voltage differences caused by movement of the electrode cables are a lot harder to control. The most important source of noise during EEG-recordings is the subject itself, because not only the brain produces voltage differences. Also muscles (MEG) or the Heart (ECG) create potentials that can influence the EEG-recording. The most sensitive part of the system, the electrodes can also be responsible for artifacts for example due to sweating or movement.

3.1.3 Electrode System

For all EEG-applications, such as clinical of tor research purposes, it is very important to know over which areas of the brain a specific electrode is located. Since the head does not show a great number of anatomical landmarks, finding certain electrode-positions was very difficult. In order to standardize electrode-placement, the international Federation of Societies for Electroencephalography and Clinical Neurophysiology established the conventional electrode system (also called 10-20

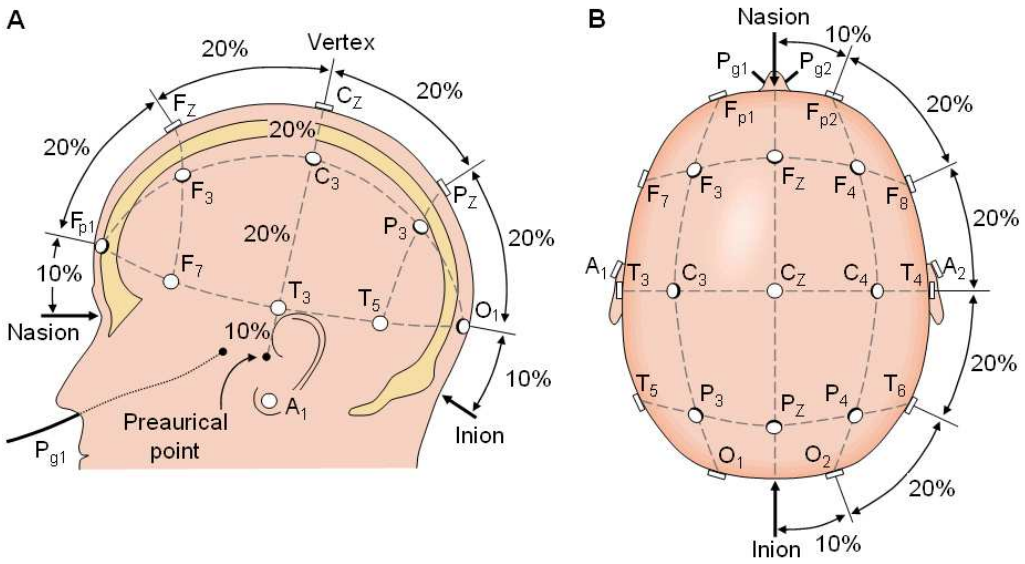

Figure 2: Visualization of the 10-20 electrode positions(http://www.bem.fi/)

system) for 21 electrodes. This system uses anatomical landmarks (Nasion and Inion) and aligns electrodes along this axis in 10- or 20% of the total distance. Figure 2 shows the electrode placement on the head according to the standardized rules. Electrodes that are located on left and right hemisphere are aligned in the same manner at an axis between the two Preauricular points, which are located in front of both ears. Since the standardized electrode placement is only established for 21 electrodes. However many modern electrode systems have larger number of channels like 65 or 129. In order to retain the 10 - 20 electrode systems the additional channels are located in the spaces between the original 21 electrodes.[2] Figure 3 shows all electrode positions for the EEG-system used in this study. In order not to be forced to align all electrodes manually, special EEG-caps are used. These caps have similar shape to a bathing cap and have holes for each electrode. This provides easy reproducible electrode positioning over many patients. The electrodes itself are a crucial part of every EEG-system as they provide the electrical connection to the scalp. The quality of EEG-data is highly dependent on low and steady impedance of about 5kΩ. In most modern EEG-systems the electrodes are reusable and made of materials like stainless steel, gold or tin.[2] After placing the electrode on the scalp the impedance is lowered afterwards using conducting electrode gel. The big advantage of this type of electrodes is, that the metal part does not have to directly touch the scalp because the gel provides contact. Therefore long hair does not have such a

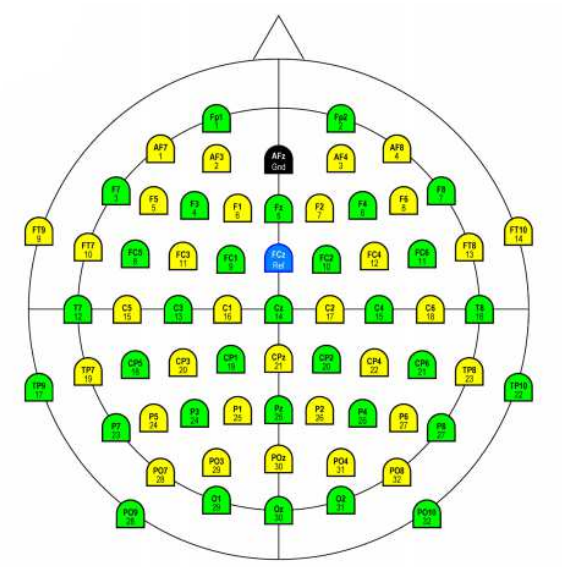

Figure 3: Electrode locations for the used EEG-system(http://www.brainproducts.com/)

high influence compared to older electrodes like disposable pre-gelled types. Due to the fact that electrical brain-signals have a very low amplitude, they can be highly affected by many different kinds of noise. The cables leading from the electrodes to the amplifier were an ideal point of attack for electromagnetic interference. Even moving the cables during recording the EEG could add undesired noise. In order to counter this, newer EEG-systems use active electrodes. These Electrodes contain simple amplification circuits and therefore rise the amplitude of the recorded signal until it is transmitted over the electrode-cable to the actual amplifier.

3.1.4 Referencing

For EEG-recording two different models of recordings, namely differential and referential, are used. In the differential method potentials are calculated as differences between two electrodes. The referential method thereby uses one or more references to which every other electrode is compared. Those references can be for example the nose, the ear lobes or an EEG electrode itself. The central Cz electrode is often used for this purpose. Another method is to re-reference the recorded signal to an overall reference, which is created by calculating the average signal of all electrodes.

3.2 Signals and Physiological Representation

The human Brain and in general the CNS (Central Nervous System) consists of nerve cells called neurons. Neurons can respond to stimuli reaching the cell through branch-like dendrites by sending its own stimulus through the axon which is a long cylindrical process also attached to the cell body. Each neuron consists of one cell body, multiple dendrites and one axon. Figure 4 shows a nerve cell.

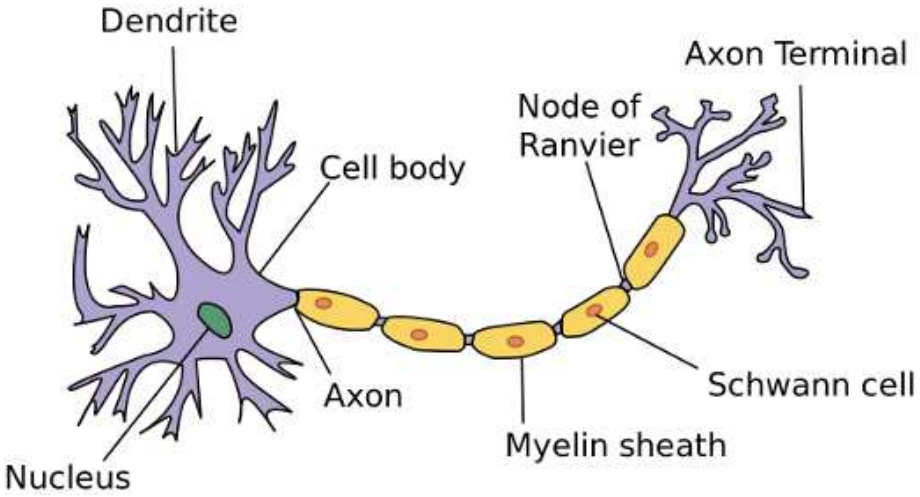

Figure 4: Neuron with Dendrites, Cell Body and Axon.(http://training.seer.cancer.gov)

In order to transmit information from one cell to the other, Neurons can discharge with a potential of -60 to -70 mV by exchanging cations and anions from the inside of the cell to the outside and vice versa. This change in potential also called action potential along the axon of a nerve cell causes a field potential in the Frequency range of less than 100Hz. Those field potentials are the basis for the EEG. But what is actually measured, when the EEG is recoded is the resulting electrical field caused by the currents of millions of neurons over the brain. In order to be able to measure the EEG with electrodes on the scalp, this signal still has to pass through the scull which has an impedance that is about 80 times higher than the electrical resistance of the brain or the scalp.[2] For this reason, electrodes can also implanted surgically under the scull to maximize amplitudes. Due to the fact that only the resulting potentials can be measured, nerve cells firing at the same time in opposite directions would compensate themselves. Therefore only larger populations of neurons facing in the same direction can create a signal that is strong enough to be measured signal.

Band	Frequency	Association	Amplitude
Delta(δ)	0,5-4 Hz	Appear during deep sleep, sometimes during waking state.	>100μV
Theta (θ)	4-7,5 Hz	Consciousness towards drowsiness	>50μV
Alpha (α)	8-13 Hz	Relaxed awareness but no concentration. Especially prevalent when eyes closed.	<50μV
Beta (β)	13-26 Hz	Associated with awareness, excitement and thinking.	<30μV
Gamma (γ)	>26 Hz	Related with movement tasks and certain active brain areas.	very low

Figure 5: EEG-Frequency bands and their physiological interpretation

An example for such cell groups is the pyramid cells of the motor cortex.

3.2.1 Frequency Bands

In healthy adults the EEG shows a broad variety in frequency and amplitude and is changing from one state to the other, for example wakefulness and sleep. The five major wave types are distinguished by their frequency ranges. These frequency bands are called delta (δ) theta (θ) alpha (α) beta (β) and gamma (γ). The bands which were first detected, are alpha and beta waves. Those were first introduced in 1929 by Berger. The other bands were found later due to better recording techniques. Certain frequency bands are associated with different conditions like the alpha rhythm which is prevalent while having eyes closed but being awake. Table 3 shows the different bands and their frequency and gives information about the factors that influence them.[2] Due to the fact that these bands can be at slightly different frequencies in different people, the frequency of an oscillation is always added when mentioning different bands. The bands can also be defined slightly different depending on the literature. In more recent publications the definition of individual bands is also often dynamic which means that the frequency of the most prevalent oscillation is taken as a reference for calculating the bands.[3] In most cases though, the estimate definition of a specific band is sufficient. A possible explanation for the existence of different frequency bands, is that the frequency of the oscillations is negatively

correlated to their Amplitude. For example delta- and theta- rhythms show much higher amplitude than the much faster gamma-band. This effect is considered to be caused by the finding that slow oscillating neuronal networks consist of more cells than faster oscillating cell assemblies.[4]

3.2.2 Event related Potentials

Event Related Potentials (ERP) are potentials in the Brain that occur related to specific internal or external events for example stimuli, or more abstract processes like decisions. They are widely used in research and clinics. Different event-related potentials are usually named after the voltage of the component. N- is used for negative potentials P- is used for positive signals and the latency after a stimulus, usually in milliseconds. ERP can be divided into several subcategories. Exogenous sensory components are obligatorily triggered by the presence of a stimulus. Endogenous components reflect neural processes that are entirely task-dependent and motor components accompany the preparation and execution of a given motor response. ERP components can occur language-related, visually-related, auditory-related, or emotion-related. For example special component called Bereitschaftspotential (readiness-potential) which will be discussed more in later paragraphs appears as a strong negative wave that appears before voluntary limb movement onset disregarding the execution of the movement itself. This effect can for example be used for brain- computer interfaces. Like the other components of the EEG, the neural origin of ERP lies in the discharge of neurons, creating a dipoles, that, when summed together can change the potential on the scalp. To create a signal, firing neurons have to be aligned similarly, so that the potentials do not cancel out. The cortex of the human brain consists mostly of pyramidal cells, which fulfill that requirement. ERP are extracted from the EEG-activity by averaging over a great number of trials. This is necessary because the potential of a single ERP is too low to be detected. Averaging is possible because ERP are time- and phase- locked[5], which means that for example a positive potential caused by a certain area appears at the same time as a positive potential caused by neighboring structures and therefore sum together. Any potential that is not phase-locked gets more or less zeroed out by adding more and more trials. A good explanation for this phenomena is given in [6] as figure 6. The left column shows the effects of averaging on a signal containing phase-locked and non phase-locked parts.

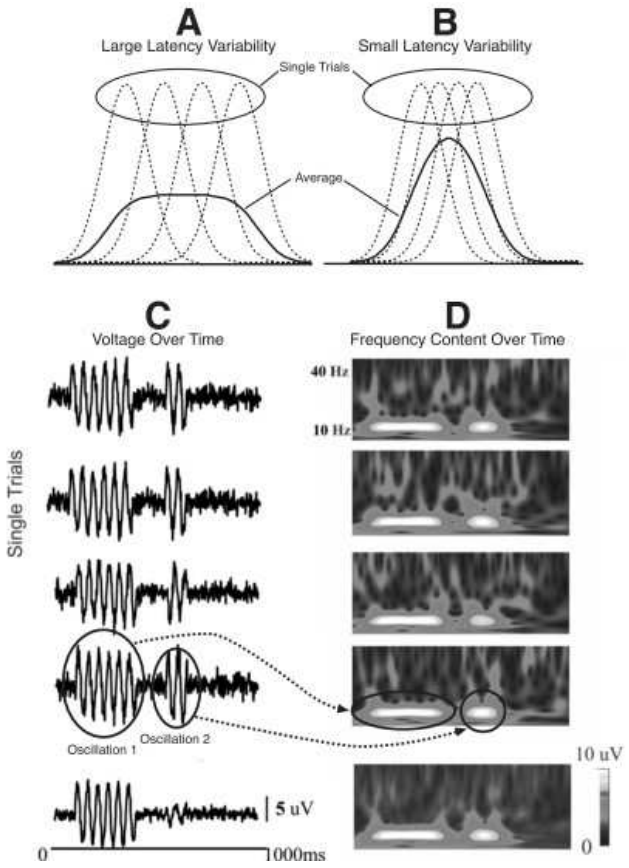

Figure 6: Effects of averaging on phase-locked and non phase-locked potentials

A common method for the quantification of ERP is additive averaging over trials using the formula in equation 1 for a dataset containing N trials.

$$ERP_{(j)} = \frac{1}{N} \sum_{i=N}^{i=1} x_{(i,j)} \tag{1}$$

Where x(i,j) = j-th sample of the i-th trial of the data set. This method suppresses the non-phase-locked activities in the signal and is therefore not applicable for detection for event-related-oscillations that will be discussed in the next paragraph.[5]

3.2.3 Event related Oscillations

Event related Oscillations are non-phase-locked components of an EEG-signal. They can therefore not be found by linear methods like averaging. The first finding of a re-

lated effect was made by Berger(1930), who discovered that opening the eyes during relaxed state and other events can reduce alpha activity. Event related oscillations can appear as ether increase or decrease of power in specific frequency bands. An explanation for this effect is increasing or decreasing synchrony of the firing of groups of neurons which is influenced by effects. Because of this assumption, event related Oscillations are separated into ERD (Event-Related-Desynchronization which leads to decreasing band power) and ERS (Event-Related-Synchronization leading to increased band power). In contrast to ERP, these effects are considered to be caused by changes in several influences controlling oscillations in neuronal networks and are caused by the cortex. [4]. Figure 7 shows the different areas that cause evoked and induced cortical activity.

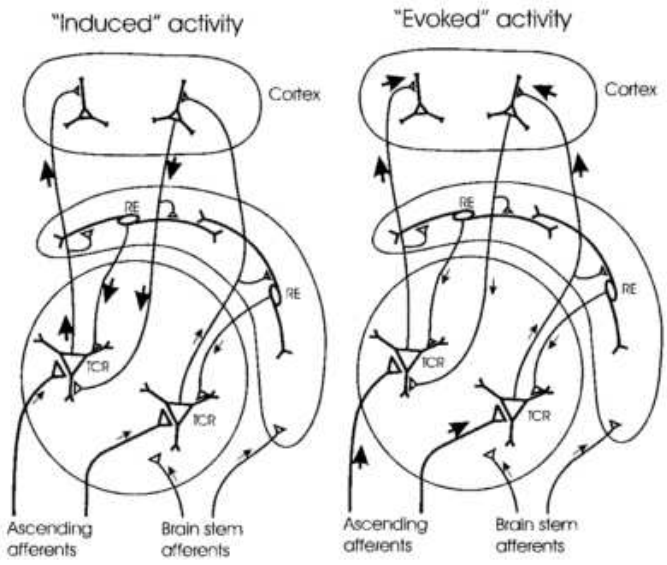

Figure 7: Difference between induced and evoked activity [4]

Quantification of ERD- and ERS- signals cant be done using linear methods due to the fact that these oscillations are not phase-locked but jut time locked. A more traditional approach is the calculation of power relative to a baseline period. This method contains three main steps [5][4]:

- Bandpass-filtering of all trials in order to be able to focus on the desired band
- Squaring of the amplitude of each sample in order to get the power described in equation 2: N is the number of trials, while x is the band pass filtered signal.

- Calculation of the power relative to a certain baseline in percent of the baseline

$$\overline{P_{(j)}} = \sum_{N}^{i=1} x_{(i,j)}^2 \tag{2}$$

This classical approach shows results in most cases but has the disadvantage, that phase-locked oscillations are still present. Especially when the focus is on lower frequency components, these phase-locked activities can mask the underlying ERD/ERS. To avoid that a different approach is the calculation of tintertrial variance[5]. This method also contains 3 major steps:

- Band pass filtering identical with the first approach
- Calculation of intertrial variance to reject phase-locked components described in equation 3.
- Calculation of ERD by calculating percentage of the baseline according to equation 4. With R = averaged intertrial variance of the baseline period.

$$IV_{(j)} = \frac{1}{1-N} \sum_{i=N}^{i=1} \left\{ x_{(i,j)} - \overline{x}_{(j)} \right\}^2 \tag{3}$$

$$ERD_{(j)} = \frac{R - IV}{R} \times 100\% \tag{4}$$

The two methods have in common, that in order to detect ERD/ERD a reliable baseline has to be present. In many cases it is difficult to estimate the minimum time between trials in order to get a good baseline. In cases involving limb movement, the time between trials should be at minimum 10s long.[4]

3.2.4 EEG during Movement

In the past, many researchers were concentrating on the effects of movements of different limbs on the EEG. One major reason for this is the intention to find signals that can be valuable for controlling brain computer interfaces using the imagination of limb movements. Despite that field, the EEG-signals caused by movements help to provide valuable information about how the brain controls motor activity. Most of the processes happening in the brain are located in the so called motor cortex. The sensorimotor cortex is located around the Central sulcus of the cerebral cortex. The

Precentral gyrus is thereby responsible for motor performance and the Postcentral gyrus for sensory signals. Figure 8 shows the major lobes of the left hemisphere of a human brain with the mentioned corti.

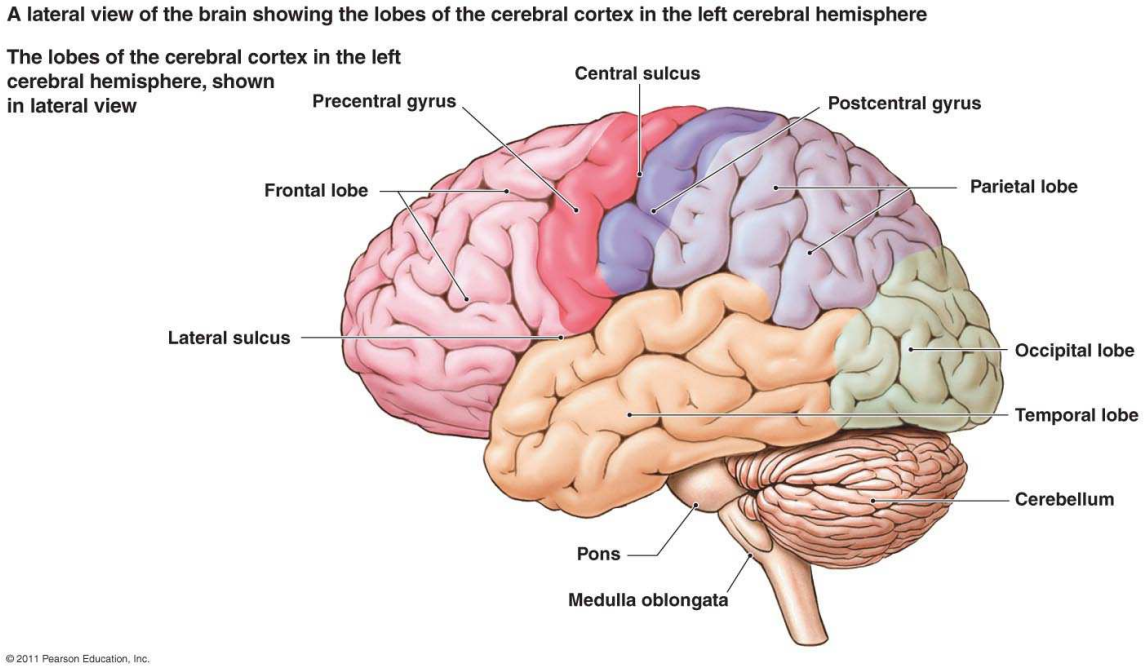

Figure 8: Cerebral sections (left hemisphere)

The representation of different limbs and muscles is depending on the region in both gyri. In figure 9 which shows the cortical homunculus, the different body parts are projected over both Precentral (right, responsible for motor activity) and Postcentral (left responsible for sensation) areas. It is clearly visible, that the upper limbs have very dominant fractions of both motor- and sensory cortex.

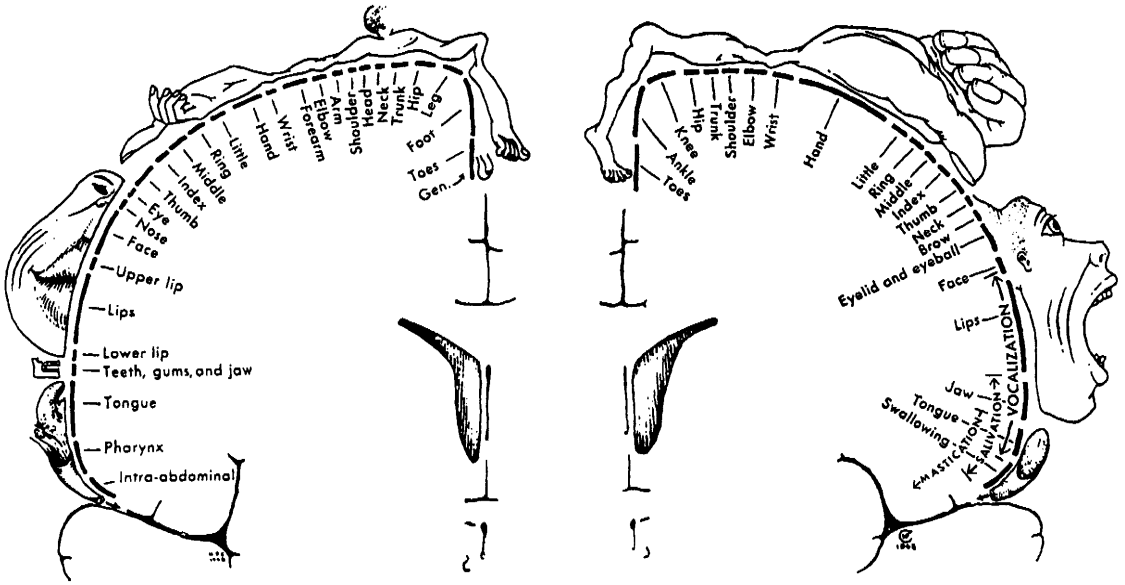

Figure 9: Cortical humunculus: postcentral (left) precentral (right) (http://humanphysiology.academy)

When a person performs movement with an arm or a leg, the specific part of the motor cortex associated with this extremity becomes more active. Thereby it is important to know that the part of the cortex responsible for a specific limb is always located on the opposite hemisphere. Right hand movement for example controlled by the motor cortex of the left hemisphere. Like motor control, also sensory stimuli lead to the activation of the opposite sensory cortex. Studies have shown, that the activation of the motor cortex during the preparation, execution, and even imagination of movements produce event-related desynchronization over those areas. Especially the so called mu-rhythm (10Hz) which is part of the alpha band, and the beta band at about 20Hz are known for decreasing power associated with movements. The decrease in the alpha band is also often followed by an increase (ERS) in power. [7] This increase is considered to represent decreasing activation of cortical areas after movement or sensory stimuli.

3.3 Effects of Tendon Vibration on Sensation

The purpose of this paper is to examine the effects of tendon vibration during movement on the activity of the human brain. Therefore a number of existing experiments show that mechanical vibrations in specific frequency ranges can influence receptors

in muscles responsible for proprioception. Those receptors are called muscle spindles. It is for example known that high frequency vibration applied longitudinally to the excised tendons of experimental animals or transversely through the skin in humans excites muscle afferents under isometric conditions. Muscle spindle group Ia afferents are known to be most sensitive to vibration.[8] Even though before focusing on the neurological effect of vibrations, it is useful to take a view on existing experiments and publications showing the direct effects of tendon vibration on precise movement control in humans.

3.3.1 Brief Tendon Vibration

When tendon vibration is applied only during the execution of a specific movement task no longer than 10 seconds, it causes a number of effects observed in different studies. The most investigated are illusory movements evoked by vibration. For example, vibration at frequencies >20Hz can lead to wrong perceptions of the angle of the affected joint. [8] When vibration is shut off, a returning illusory movement can be provoked. However, more interesting than those movement illusions are the effects of vibration when applied during tasks that require precise movements, especially with patients suffering from sensory deficits for example caused by stroke. It was demonstrated that activation of wrist proprioceptors through tendon vibration at the wrist can significantly improve stability of the entire hemiparetic arm after goal-directed precise arm movements. [9] [10]. This also shows that the vibration applied at the wrist can influence muscles responsible for upper arm or even shoulder movements. It is expected that in those cases tendon vibration affects muscle Ia-afferents and thereby the sensory cortex in a matter of increasing sensory input, which facilitates fast and precise movement tasks.

3.3.2 Prolonged Tendon Vibration

In contrast to brief tendon vibration prolonged vibration is applied over longer times disregarding if there is movements to execute or not. Prolonged vibration shows effects that are in some respects contrary to the effects of shorter tactile stimulation. It can reduce excitatory Ia afferent input from the affected muscles and can even lead to reduced MCV (Maximum Voluntary Contraction) force or slight numbness. These effects appear when the muscle is affected more than 10-20 seconds by the vibration and can be explained by fatigue of the muscle spindles. [11]. The effect of prolonged tendon vibration disappear shortly after vibration is shut off.

4 Experiment

4.1 Conception and Aim

The aim of experiment which was carried into execution during my stay at Marquette University was to observe the influence of brief and prolonged tendon vibration on the human brain, especially during sensorimotor performance. The objective was to find possible reasons for the known effects of tendon vibration at a cortical level by focusing also on non-voluntary movements. Furthermore the intention was to show coherency between sensory stimuli and motor performance by comparing the effects of different conditions on the α- and β- frequency bands in the EEG.

4.2 Materials

All the equipment that was needed in order to run the experiments described were provided by the INRL(Integrative Neural Engineering & Rehabilitation Laboratory at Marquette University. Most of the devices needed, were already built or acquired for previous experiments like the arm robot described in section 4.2.2 or the EEG Device. Even though after a number of pilot tests, some details had to be modified in order to minimize interference or other negative effects between the devices.

4.2.1 EEG Device

EEG was recorded during the trials using a 64-channel EEG-system with active electrodes (actiCAP, Brain Products, Germany).The electrode positions were according to the international 10-20 coordinate system with a reference at FCz and a ground at AFz. During the experiments, the electrode cap was placed on the subjects head so that the Cz electrode was located over the vertex, in line with the the prearticular points of each ear in the frontal plane and with the nasion and inion in the sagittal plane. Impedance between electrodes and scalp was reduced under 10kΩ by injecting electrode gel (SuperVisc gel, Brain Products, Germany) under each electrode. In figure 10 the placement of the EEG-cap is demonstrated.

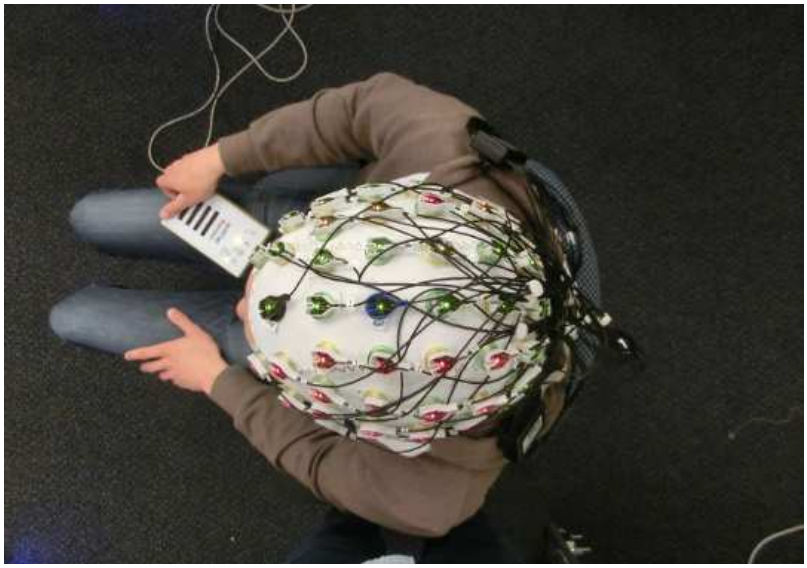

Figure 10: EEG-cap on a subject's head (LED's on each electrode show it's impedance)

Due to the active electrode design, each electrode shows it's impedance with a small light emitting diode. If the impedance is too high, which means that there is no good contact between electrode and the scalp the electrode is red. As soon as the impedance is reduced under 10ω, for example by injecting more electrode gel, the light turns green. This feature of the electrodes is very useful and helps setting up the system faster. Figure 11 shows a single electrode in detail. The electronics of the small amplifier is visible through the synthetic resin. The small opening on the right side of the electrode allows the injection of the electrode gel using syringe with a blunt cannula.

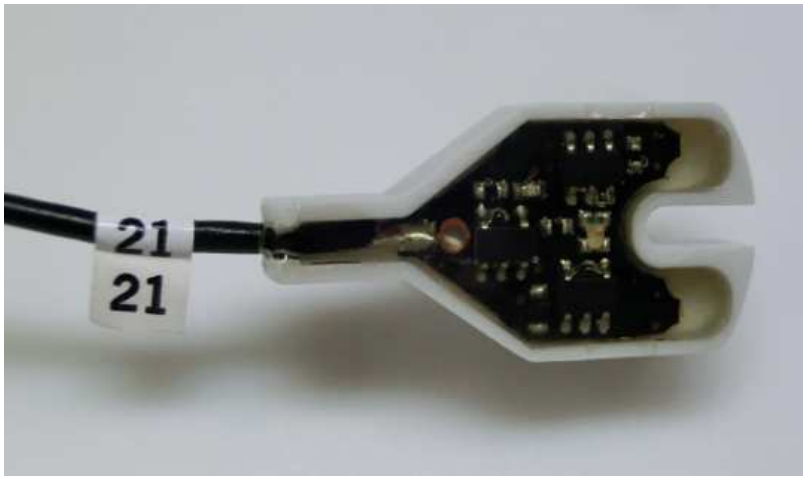

Figure 11: Active electrode of the used EEG-system (actiCAP, Brain Products, Germany)

EEG-signals were recorded, amplified and sampled at 1000Hz. The signals were also bandpass-filtered between 0.1 and 200Hz using a Synamps system (Neuroscan, Charlotte, NC) and recorded using the Neuroscan Scan 4.5 software (Neuroscan, Charlotte, NC).

4.2.2 Arm robot system

For the study a planar robot consisting of a 5-bar linkage arm was used. The construction, which was already used in previous studies[9] allows the subjects to move their arm freely in 2D space. An overhead projector was used to display the instructions, hand- and target positions on a horizontal screen, located directly over the field of motion. Pilot studies have shown that even though the subjects did not have to move their head in order to perform the tasks, movement artifacts are visible in the EEG. To minimize those negative signals, a chin rest was added to the horizontal screen which allowed the subjects to relax their neck and helped them to remain steady for longer periods of time. Figure 12 shows the arm robot system and its different components.

Figure 12: Arm robot system with horizontal screen (projector is mounted on the ceiling over the system)

4.2.3 Tendon vibrator

The tendon vibrator used in the experiment was a custom made tendon vibrator consisting of an offset mass rotated by a small electric motor (Dr Fritz Faulhaber GmbH & Co. KG, Schnaich, Germany). The motor was controlled to keep a constant speed in order to vibrate at 80Hz During all trials in the experiment this motor was affixed with tape over the wrist flexor (WF) tendons of the subject. Figure 13 shows the anatomy of the wrist.

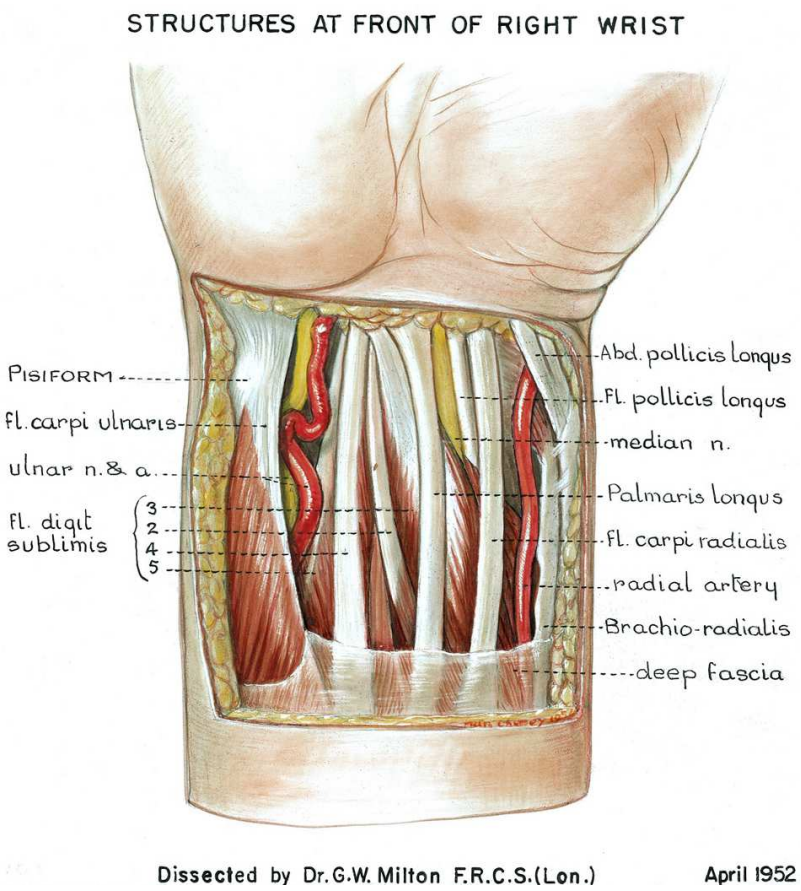

Figure 13: Anatomy of the wrist wiht tendons affected by vibration (http://clinicalanatomy.ca/)

Even tough the vibrator affects mostly the tendons located directly under it, the vibration also influences the more distant tendons of the lower- and even the upper arm. During a number of pilot studies subjects were stating that the vibrator was becoming too warm after a number of trials especially during prolonged conditions. After some tests and analysis of the EEG-signal, it turned out to be that the frequency of the vibration was 90Hz instead of the intended 80Hz. Because of that, the motor ran faster than intended and thereby produced more heat. After adjusting the turning speed the problem with the high temperatures could be solved. A different problem with the motor was electrical noise. Even though it had some basic insulation, the motor seemed to cause noise in the EEG-system. For this reason motor and cables were additionally shielded. Figures 14 and 15 show the motor before- and after the shielding. By that, the electrical noise could be reduced to a level which

was no more recognizable by the EEG-device.

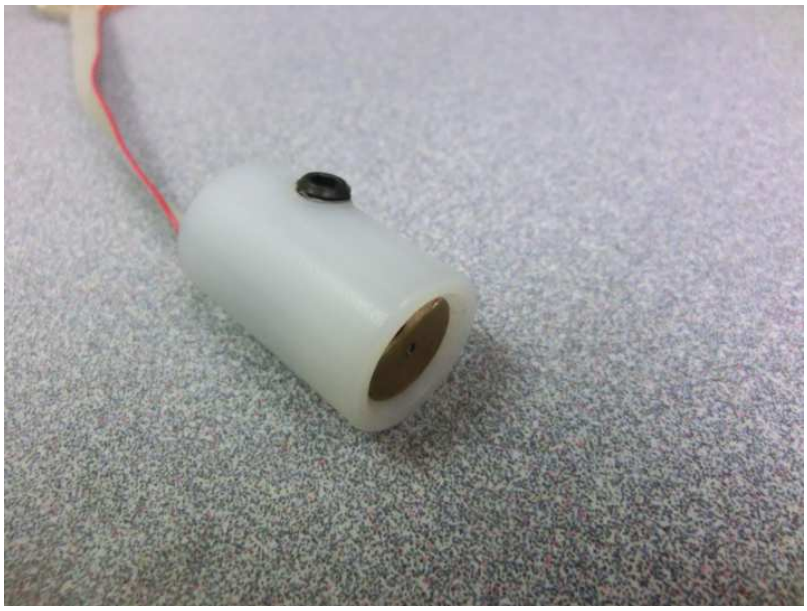

Figure 14: Tendon vibrator without insulation (acentric weight is visible in the front)

Figure 15: Tendon vibrator after insulation

4.2.4 Software

For implementing the protocol, data collection and data analysis, a number of different programs was used. The arm robot described in section 4.2.2 was programmed in LabVIEW(National Instruments Corporation, USA) so the protocol had to be integrated using the same software. Therefore already existing programs were modified in order to create the desired protocol. Figure 16 shows parts of the program that were modified. The code shows the activation of the vibrator after a relax time of 8seconds (magenta wires) and the end of the relax period after 10 seconds. Beside presenting and running the protocol, the program also collects position data of the arm robot and provides a cue for the EEG-device which represents the start of every movement period.

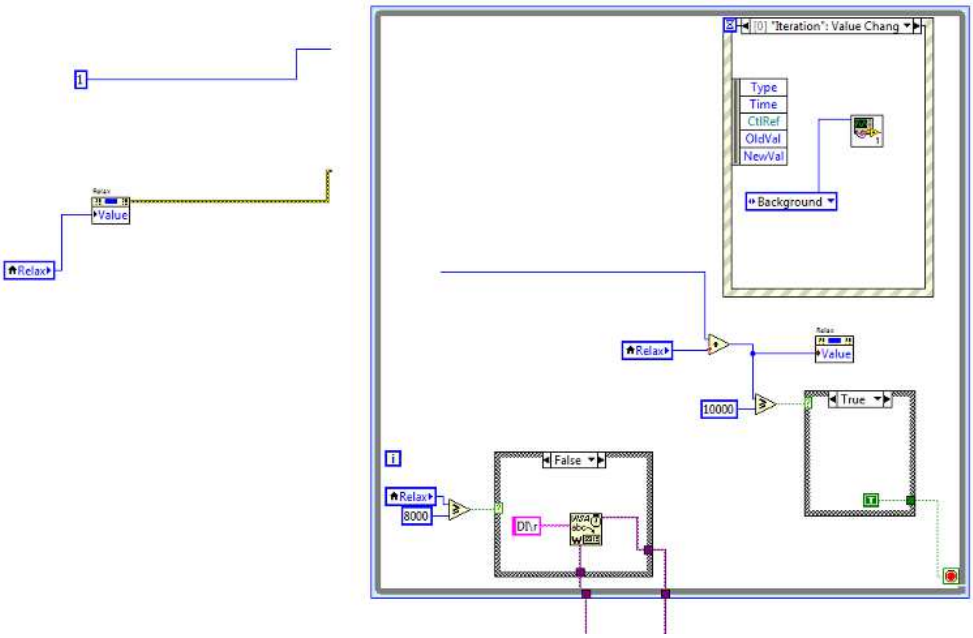

Figure 16: LabVIEW program controlling the tendon-vibrator

The actual processing of the EEG- and movement data was then programmed in MATLAB(The MathWorks, Inc. , USA) by using the open source toolbox EEGLAB[12], which is specially designed for EEG-analysis. Further processing, source localization and visualization was then done using BRAINSTORM [13]. Programs and further information is given in section 4.4.

4.3 Methods

In the experiment 10 subjects had to perform simple point to point reaching tasks between two circles (r = 5cm). Visual feedback was given by a white cursor circle (r = 0.5cm). At the beginning of each trial participants had to move the cursor by manipulating the arm robot to the white home circle. After reaching this position both home circle and cursor disappeared and an eight second relax-period marked by the word RELAX projected in the middle of the screen was started. Two seconds after the RELAX sign disappeared a red target circle appeared at a distance of 30cm from the former home circle and a trigger signal was sent to the EEG-system. Participants were then instructed to move as quickly as possible from home position to the target circle and hold the cursor inside the circle until the target disappeared. (2 seconds after reaching the target).

4.3.1 Participants

10 healthy young right handed adults (6 male, 4 female, average age 24) participated in this study. No history of neurological disease or injury was reported by any of the participants. The participants stated to feel rested when starting each condition. Written informed consent was given by every subject and the experimental protocol was approved by the Marquette University Institutional Review Board to be in accordance with the Helsinki Declaration of 1975.

4.3.2 Conditions

In order to examine the effects of brief and prolonged tendon vibration and to be able to compare them with each other, an experiment protocol was established. The protocol contained 6 different conditions with a total of 30 arm-movement trials each. Conditions consisted of the combination of two factors: Volition (active and passive conditions) and Duration of Vibration (no vibration, brief vibration, prolonged vibration). During active conditions the participant had to move his arm independently only using the visual feedback he gets from the arm robot. Conversely, the subject was told to relax while his arm was moved by manipulating the mobile arm rest connected with the robot. In conditions without vibration, the vibrator was not activated and remained passively at the subjects wrist. In Conditions with brief vibration the vibrator was activated 2 seconds before appearance of the target circle and stopped two seconds after reaching the target, contrary to the conditions with prolonged vibration in which the vibrator was activated permanently.

4.3.3 Sequence

Each session included all 6 conditions combining the different factors described in section 4.3.2. In order to minimize the eventually existing long-term effects of the vibration on the central nervous system, trials were executed in the order: no vibration, brief vibration, prolonged vibration. Active and passive conditions of each vibration type were then executed in a random order. Every subject had to perform all conditions in one session. Figure 17 illustrates the experimental protocol with all 180 cycles.

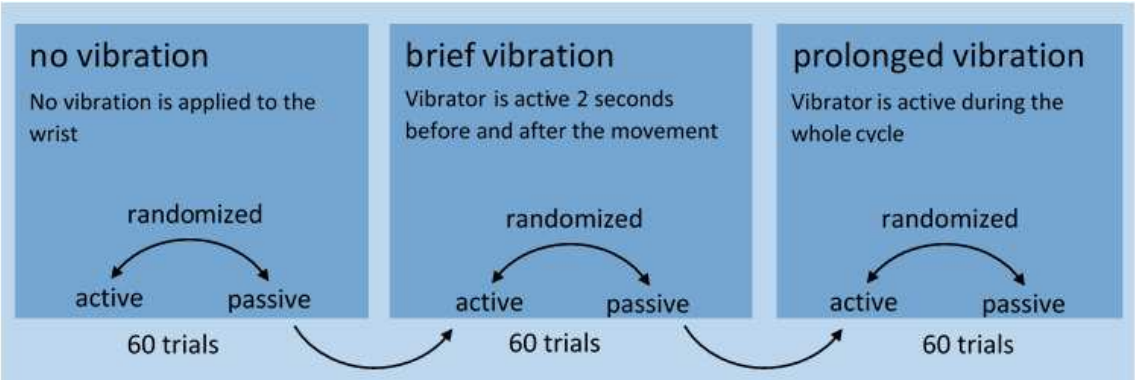

Figure 17: Protocol for one subject

4.4 Data Analysis

Besides the collection of data and the design of the whole study, data analysis is the most important factor in an EEG-experiment. Without proper methods for finding certain elements in the signal, the EEG is mostly meaningless noise. The processing in this study was done in three mayor steps. In the first step, the preprocessing, the data was epoched filtered and referenced. In a second step Independent Component Analysis was applied in order to be able to reject components which can be considered as noise or artifacts. The now cleaned EEG-data was then examined for example to detect β-band Desynchronization or the changes in slow potentials. As a last step, the data was again processed in order to get source localized signals. In the following paragraphs, all steps are again explained in more detail.

4.4.1 Preprocessing

EEG recordings done with the used EEG-device are stored as continuous Neuroscan files (.cnt). All 30 trials of one condition are stored continuously, so one of the first

```
% Epoch EEG Data
EEG = pop_epoch( EEG, {  '4'  }, [-5  3], 'epochinfo', 'yes');
EEG = eeg_checkset( EEG );
```

Figure 18: Epoch function in EEGLAB

```
EEG.lowpassfilt = 100;
EEG.highpassfilt = 0.1;
lownotch = 77;
highnotch = 83;
Hd = fdesign.bandpass('N,Fc1,Fc2',4,EEG.highpassfilt,...
EEG.lowpassfilt,EEG.srate);
d = design(Hd,'butter');
[b,a]= sos2tf(d.sosMatrix,d.ScaleValues);

Hd2 = fdesign.bandstop('N,Fc1,Fc2',4,lownotch,highnotch,EEG.srate);
d2 = design(Hd2,'butter');
[b2,a2]= sos2tf(d2.sosMatrix,d2.ScaleValues);
% h2=fvtool(b2,a2);
% set(h2,'Fs',1000,'FrequencyRange','[0, FS/2)');

EEG.data = single(filtfilt(b,a,double(EEG.data)'))';
EEG.data = single(filtfilt(b2,a2,double(EEG.data)'))';
```

Figure 19: Filter functions in MATLAB

steps is to separate all 30 trials. This is done by using the trigger signal from the arm robot computer which is also saved in the .cnt files. This trigger signal marks the beginning of each movement period by signalizing when the movement cue appears. Therefore the code in figure 18 uses the function pop_epoch to select five seconds before and three seconds after each cue as epochs.

After epoching, the data sets are filtered using a 100Hz low-pass filter and a 0.1Hz high-pass filter to remove both high frequency noise as well as very slow potential shifts due to for example sweating. Figure 19 shows the implementation of the filters. After filtering, the baseline of the signal is removed. Thereby the time from -5 to -2 seconds is considered as the baseline because no activity is expected to be present during that time.

In the end of the preprocessing stage, bad trials are removed using EEGLAB's

```
[ EEG.icaweights, EEG.icasphere, EEG.mods ] =...
  runamica12( EEG.data(:,:), 'numprocs', 4 );
EEG = eeg_checkset(EEG); eeglab redraw
```

Figure 20: AMICA algorithm

pop_autoreject function as well as manual rejection based on variance and z-score. In total about 3 to 6 trials are removed from each condition. After saving the removed trials, the EEG-dataset is saved for further processing.

4.4.2 Independent Component Analysis

After being preprocessed, the EEG data still contains a lot of noise and artifacts. In order to prune the data further, a mathematical method called Independent Component Analysis (ICA) is applied. Using this method, the signal can be divided into a number of different components depending on the localization. Therefore ICA is also called a blind source localization algorithm. The ICA-method used for this study is AMICA (Adaptive Mixture Independent component Analysis). ICA is a statistical technique which takes recordings from an array of sensors and determines a set of source signals which are maximally independent according to a specified measure of statistical independence. Thereby a data model $X = AS$ is used, where X is the stacked row vectors from each sensor (For EEG-signals, every row in X is the data from one channel), S is the stacked row vectors of the statistically independent sources and A is the so called mixing matrix. Given X the ICA algorithm returns estimates for both A and S. The vectors in S are called independent components. [14] The independent components can then be used to reject artifacts. In the case of this study ICA was computed twice using the code in figure 20

After calculating the different sources, signals with artifacts were rejected manually. Some components like eye movement are rather simple to identify and therefore to reject, but others often contain both EEG and artifacts. Those cases have to be examined in detail. Figure 21 shows a list of 34 independent components found found by the AMICA algorithm. Activity of each component is displayed over a schematic head map.

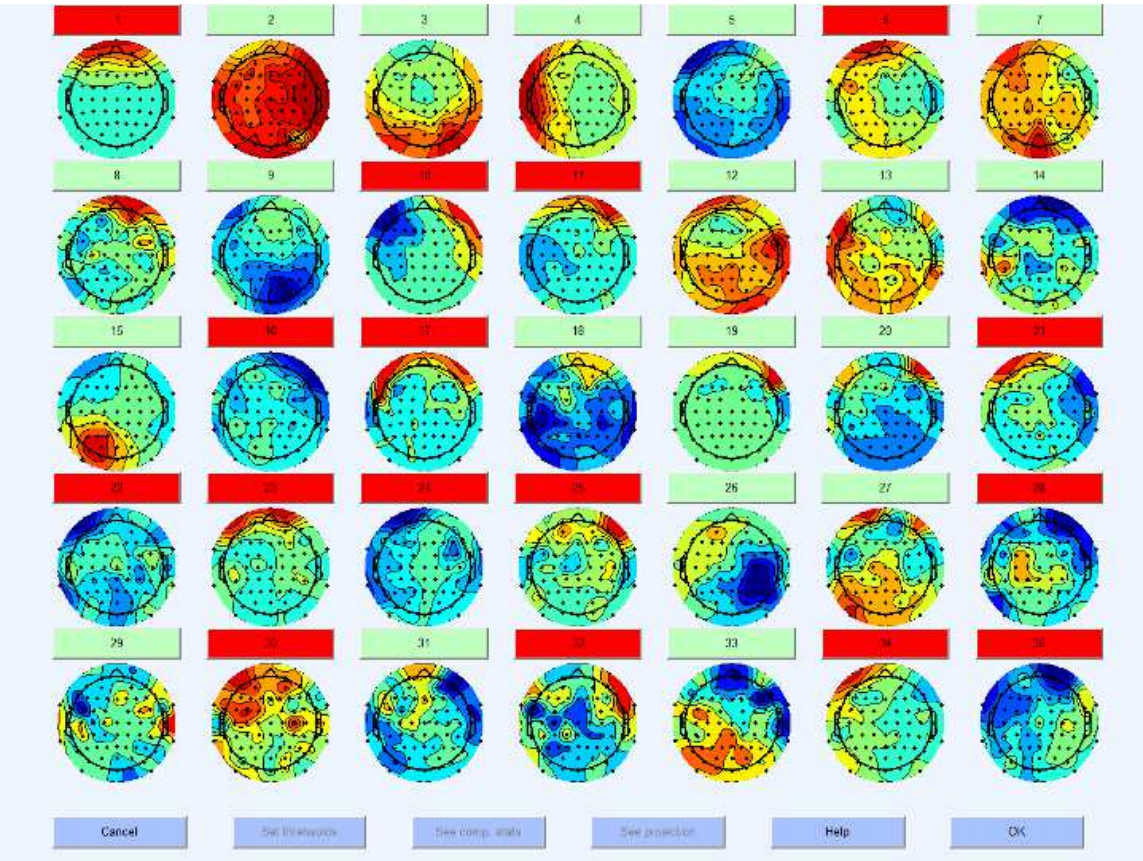

Figure 21: 35 Independent components of the EEG-signal (probable artifact components are marked red)

In order to be able to reject bad components consistently, rules were established based on the following information provided:

- **Location:** The location of the highest activity can be taken to determine for example weather it contains artifacts. If a component has high activity in the front, it is likely to be related to eye movement. If a component shows activity only in the back or the sides of the head, it is probably related to movement or muscle activation in the neck.
- **Activity over time and trials:** When the experiment protocol is known the time of the onset of a certain stimulus is known. If a component shows high activity only in times when no stimulus is present and no reaction expected it is likely to be an artifact. Also when components show high changes in activity

over trials, there might have been negative influences during a small number of trials.

- **Activity power spectrum:** It is known that the main activity of the human EEG is located around 10Hz which represents the αrythm. If a component only shows activity below 1.5Hz, it is likely to be movement related. Components showing high frequencies around 60-90Hz are often caused by MEG(muscle activation), because the main frequency of the MEG is located around 100-200Hz.

- **Spectrogram:** The spectrogram of a component can help determining weather it contains valuable information or weather it can be rejected. In most cases like the described experiment, it is known that the activity of certain bands changes with time (βband desynchronizes shortly before movement onset). Knowing this, components showing the expected effects are very likely to be brain-related. Components showing activity in frequencies which are not known for being brain-related can be considered as less important or artifacts.

When applying those rules, it is important to apply them consistently on all data sets used in one experiment. If specific components are rejected inconsistently, wrong results could be caused. It is also important to look at several factors to determine weather a component should be rejected or not. Following some prevalent common components are explained. Component 1 (figure 22) is a clear eye blinking component because of the very frontal location and the short random peaks of activity.

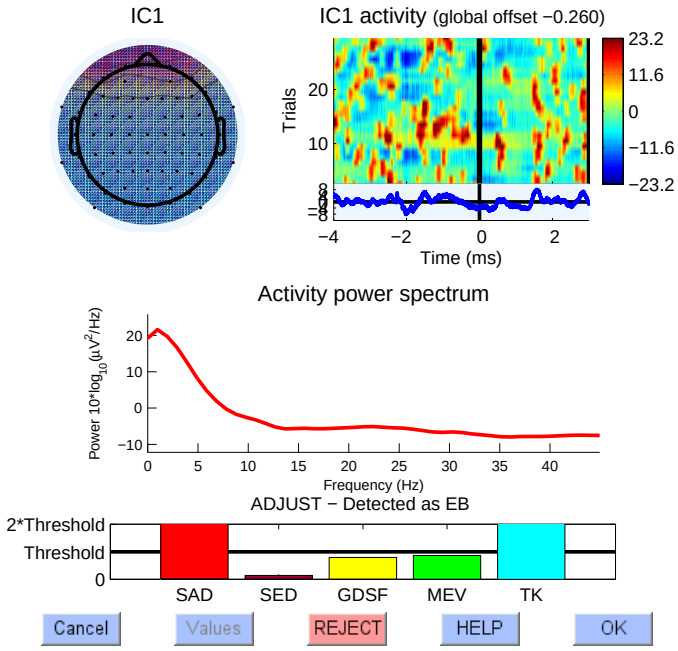

Figure 22: Eye-blinking component

By contrast, component 2 (figure 23) is an Eye movement artifact recognizable through the dipolelike topology and the also more or less random activity.

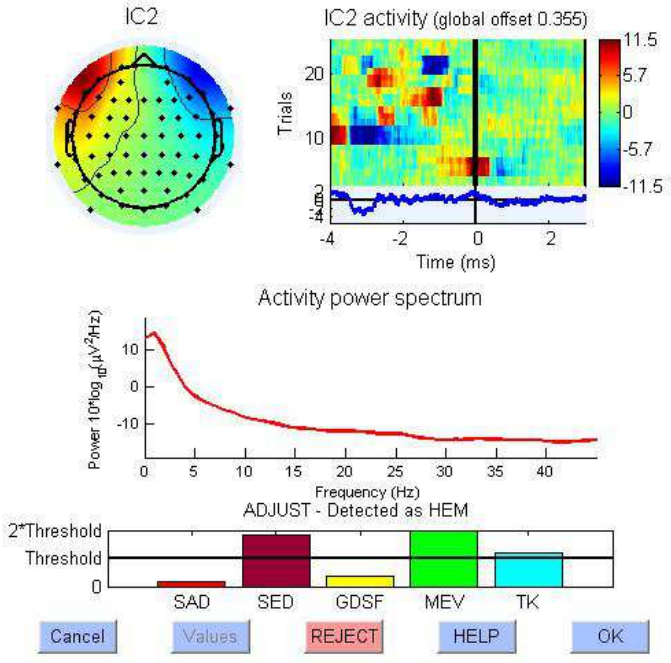

Figure 23: Eye-movement component

Component 3 (figure 24) can be considered as brain related. Its activity is centered around the right hemisphere and the power spectrum shows frequencies at 10Hz and 20Hz. By looking at the spectrogram in figure 25, it shows decrease in the α and β bands as it is expected.

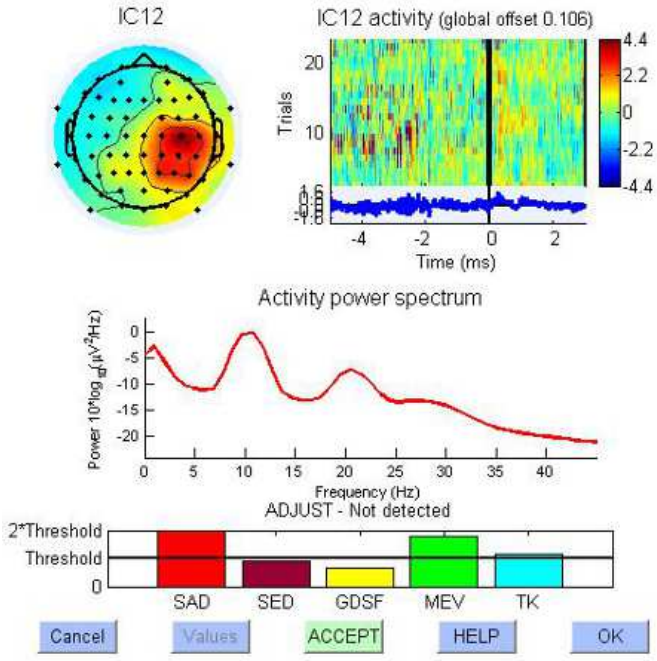

Figure 24: brain related component

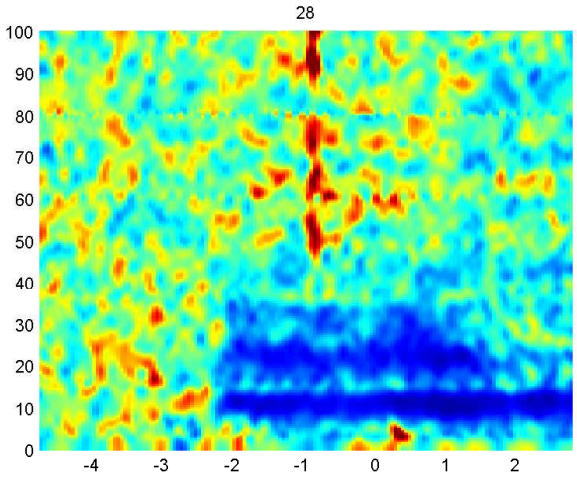

Figure 25: Spectrogram of component 3 with decreasing power in 10Hz and 20Hz

```
%Convert to Avereage Reference and add FCz reference electrode
EEG = pop_reref(EEG, [],'refloc',struct('Y',{0},'X',...
{0.39073},'Z',{0.92051},'labels',{'FCz'},'sph_theta',...
{0},'sph_phi',{67},'sph_radius',{1},'theta',{0},'radius',...
{0.12778},'type',{''},'ref',{''},'urchan',{65},'datachan',{0}));
EEG = eeg_checkset(EEG);
```

Figure 26: Re-referencing of the EEG data

After rejecting bad components, those components get subtracted from the signal. The result is a much cleaner EEG for further analysis. The data can now be rereferenced to an average reference (further explained in section 3.1.4) in order to get a signal that is less dependent on the reference electrode. The code for rereferencing the signal data is displayed in figure 26.

4.4.3 Further Analysis

After preprocessing and the elimination of artifacts by using ICA methods, the EEG is clean enough to be used for the detection of specific signals. In this case, movement-related αband and βband Desynchronizations(ERD) further explained in section 3.2.4 were detected using both methods described in section 3.2.3. The code in figures 27 to 28 shows the implementation of the classical approach using the calculation of power relative to a baseline for different frequency bands which can be selected. Once the desired frequency is chosen a Butterwoth-filter with the cutoff frequencies is applied using Matlabs filtfilt-function (line 12). This function applies the same filter twice on the signal but from different direction. By such filtering 'back and forth', the phase shift of the filter is eliminated. Also due to filtering twice, the order is doubled. Due to the fact that every filtering process causes artifacts in the beginning and the end of each data set, all trials are concatenated in lines 8 to 10 to avoid this effect.

```
1  EEGA = EEG;
2
3  [x, y, z] = size(EEG.data);
4  %x:Channels y:Data points z:Trials
5  EEG_data = EEG.data;
6  EEGs = zeros(x,y*z);
7
8  for j = 1:z
9    EEGs(:,(j*y)-(y-1):j*y) = EEG_data(:,:,j);
10 end
11
12 [b,a] = butter(order, [flow/500 fhigh/500], 'bandpass');
13 %  h1=fvtool(b,a);           %Check if order is ok
14 %  set(h1,'Fs',1000,'FrequencyRange','[0, FS/2)');
15
16 filtered_data = single(filtfilt(b,a,double(EEGs)'))';
17
18
19 for i = 1:z
20   EEGA.data(:,:,i) = filtered_data(:,i*y-(y-1):i*y);
21 end
```

Figure 27: Filter-function to select specific frequency bands

After applying the filter, the power is calculated by squaring the signal (figure 28) line 6). After that, the mean value over all trials is calculated. In order to compare the premovement period with the movement, a premovement period (-2 to 0 seconds) and a movement period (0.4 to 1.4 seconds) are defined and the band power relative to the baseline (-5 to -2 seconds) is calculated. For plotting results, the averaged signal is smoothed using a 2 Hz Butterworth low-pass filter. After applying this filter, ERD is again calculated over the entire signal. In the end, the now calculated signals are stored in matrices in order to visualize them in the next steps.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Calculate frequency band power and average across trials

motor_cortex=[8,9,13,18,19,43,47,48,52];
% left hemisphere (3x3 with c3 as center)
EEGA.data = EEGA.data.^2;
Avg_Signal = mean(EEGA.data,3);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Get average over the motor cortex before and during the
 % movement

Avg_premovement = 100*(Avg_Signal(motor_cortex,3000:4999)-...
mean(Avg_Signal(motor_cortex,(-e_beg+b_beg)*...
1000+1:(-e_beg+b_end)*1000),2)*ones(1,2000))./...
(mean(Avg_Signal(motor_cortex,(-e_beg+b_beg)*...
1000+1:(-e_beg+b_end)*1000),2)*ones(1,2000));

Avg_movement = 100*(Avg_Signal(motor_cortex,5400:6399)-...
mean(Avg_Signal(motor_cortex,(-e_beg+b_beg)*...
1000+1:(-e_beg+b_end)*1000),2)*ones(1,1000))./...
(mean(Avg_Signal(motor_cortex,(-e_beg+b_beg)*...
1000+1:(-e_beg+b_end)*1000),2)*ones(1,1000));
...
...
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Calc the ERD
ZeroBaseline_band = 100*(Avg_Signal(:,:)-...
mean(Avg_Signal(:,(-e_beg+b_beg)*1000+1:(-e_beg+b_end)*1000),2)*...
ones(1,y))./(mean(Avg_Signal(:,(-e_beg+b_beg)*...
1000+1:(-e_beg+b_end)*1000),2)*ones(1,y));
```

Figure 28: Calculation of band-power relative to baseline period

4.4.4 Visualization

After processing the signals, the data was plotted in order to be able to examine the the results and compare them in qualitative and quantitative ways. The first approach is to simply plot the power of one frequency band over the scalp with a diagram for each electrode. This way, band power can be examined and compared visually. The result is an overview over the entire scalp, giving an idea of how the band power is changing depending on time and location. In section 5 some of of those

plots are explained further A second step is the comparison between right and left hemisphere right before and during the movement tasks. According to literature[4], there should be higher decrease in band power in the left hemisphere (right handed movement) in the premovement period, compared to the left hemisphere. In order to test this on the data collected, 9 channels around the motor regions were averaged in time and across all subjects to get the mean band-power value for the selected band for each hemisphere. An example for the code is given in figure 29.

```
1
2  left_hemisphere = [8,9,13,18,19,43,47,48,52];
3  right_hemisphere = [10,11,15,20,21,44,49,50,54];
4
5  % Select only the active conditions
6  Ab_matrix = squeeze(Band_matrix(:,:,4,:));
7
8  % left hemisphere
9  % Select the channels needed
10 left_data_premovement = Ab_matrix(left_hemisphere,3000:4999,:);
11 % Average over the selected period
12 left_data_premovement_avg = squeeze(mean(left_data_premovement,2));
13 % Average over all channels
14 left_data_premovement_avg = squeeze(mean...
15 (left_data_premovement_avg,1));
16 % Average over all subjects
17 left_premovement_avg = squeeze(mean(left_data_premovement_avg));
18 % Calculate confidence intervals
19 left_premovement_conv = squeeze(2.262*...
20 (std(left_data_premovement_avg,0,2)/...
21 sqrt(size(left_data_premovement_avg,2))));
```

Figure 29: Averaging for comparing left and right hemisphere (only premovement and left hemisphere)

In every case of quantitative analysis, the 10% confidence intervals are calculated to show the values differ between subjects. Also the movement data from the arm robot was analyzed, mainly in order to find the actual movement onset. The cue of the arm robot device only tells when the order to move the hand was given to the subjects, but not when the subjects really started to move, so the actual position data helps to be more accurate. Figure30 shows the code that was implemented in order to find the movement onsets. The principle is two thresholds in time and

amplitude. After each cue, the time is counted between the cue and the first velocity value that exceeds 4cm/s. Using this method the mean latency (reaction time) can also be calculated to see weather the subjects fatigue in the end of the conditions.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Calculation of movement onset out of velocity data
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Savgol to smooth the data without reducing maximum values
cue_points = find(Counter>1);
movement_thresholded = find(Velocity>5);
end_point = cue_points(30,1);
Velocity_2 = Velocity(1:end_point+2000,1);
% Filter the data
Velocity_2 = savgol(Velocity_2,2,311,0,1000);
movement_onsets = zeros(30,1);
latencies = zeros(30,1);
for trial_count = 1:30

  k=0;

  while (movement_onsets(trial_count) == 0)
    if (Velocity_2(cue_points(trial_count)+k) >= 4)
      movement_onsets(trial_count) = cue_points(trial_count)+k;
    else
      k=k+1;
    end
        latencies(trial_count) = k/1000;
  end
end
```

Figure 30: Calculation of the movement onset

Figure 31 shows the movement onsets calculated by the code above. The trigger signal is marked as a red line and the detected movement onset is marked black.

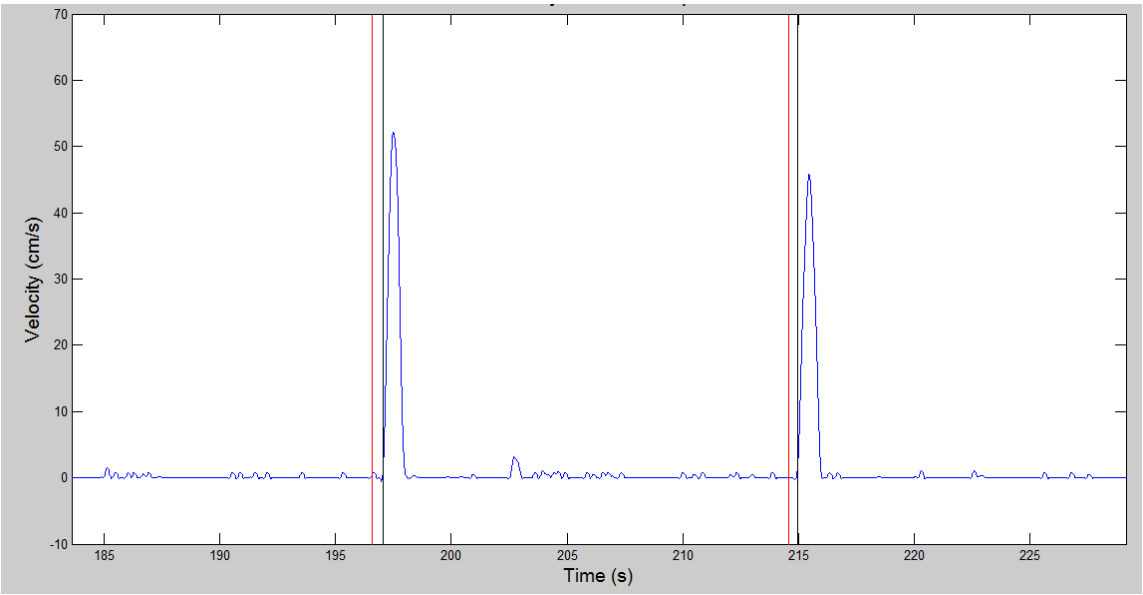

Figure 31: Velocity data: Movement onsets marked black

5 Results

In this section some of the results provided by the experiment in section 4 are explained on a reduced subject population. This section is meant to be a rough overview of our results. Other aspects of the experiment will be published elsewhere and are not mentioned in this Assignment. In order to give an overview about the changes in the EEG caused by tendon vibration during movement, two frequency bands (α- and β-band) will be discussed in the following paragraph.

5.1 Beta band

According to literature [4] movement tasks lead to desynchronization of the β-band about 2 seconds prior to movement and by a value of about 50%. This effect lasts until the movement is executed and is understood as preparatory activity of the motor cortex. For hand and finger movements, high resynchronization (>100%) was observed in prior experiments. The desynchronization is known to be lateralized in the premovement period. The experiment shows quite similar results as illustrated in figure 32. For the cases when the subjects moved actively without the application of tendon vibration, a slight decrease of the β-band can be observed around the movement cue, but no resynchronization is present.

Figure 32: β-band power over all electrodes is displayed as % of the baseline period (-5 to -2 seconds): Desynchronization is visible between -1 seconds prior the cue to 2 seconds after the cue, however resynchronization can not be observed.(Average over 5 subjects)

Figure 33 shows the lateralization of the power decrease in more detail. In the premovement period, more lateralization can be observed.

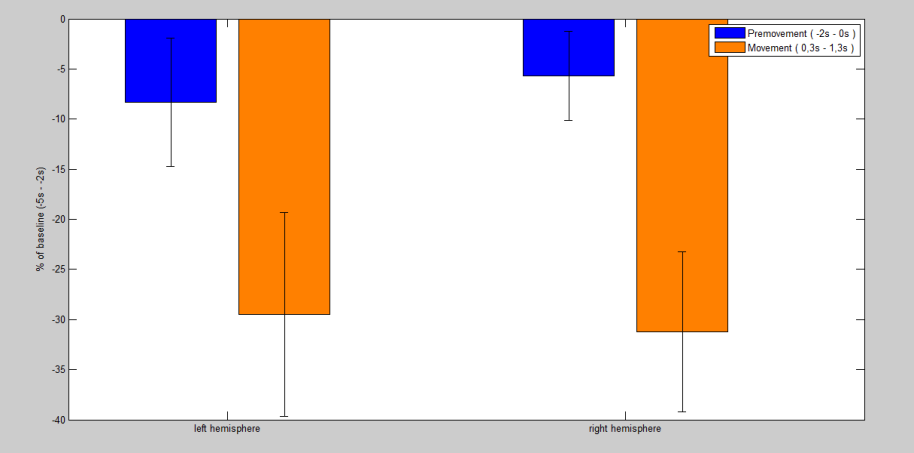

Figure 33: Comparison of left and right motor areas in both premovement- and movement periods

In the cases of passive movements, the result is very similar. Figure 35 shows that the amplitude of the band power changes is lower than in the active cases and that the premovement period is no longer affected. This goes in line with observations made in previous studies focusing on the EEG during passive movements. [15]

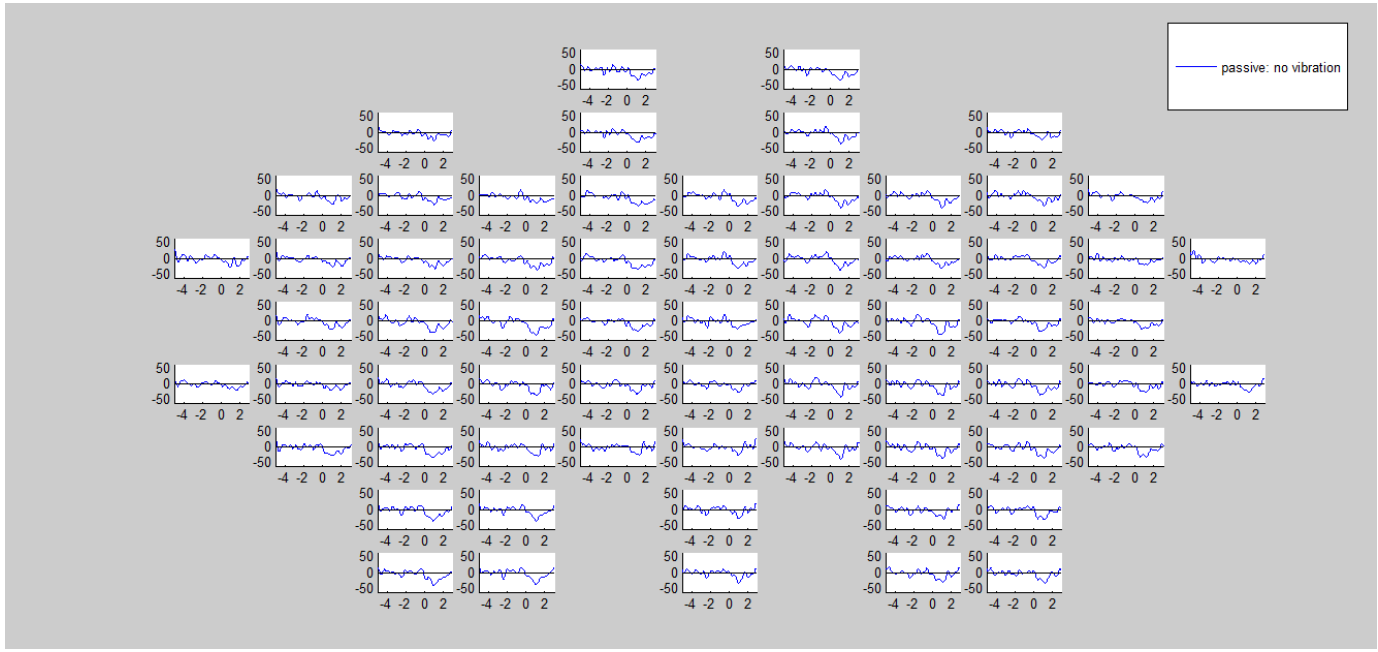

Figure 34: β-band power over all electrodes is displayed as % of the baseline period (-5 to -2 seconds): Desynchronization is visible between 0 seconds prior the cue to 2 seconds after the cue. Amplitude is lower than in the active cases.(Average over 5 subjects)

When comparing the active conditions with different types of tendon vibration, brief vibration seems to cause desynchronization of the β-band happening earlier than in the other two cases. Prolonged tendon vibration does not show a difference to the cases without the application of vibration.

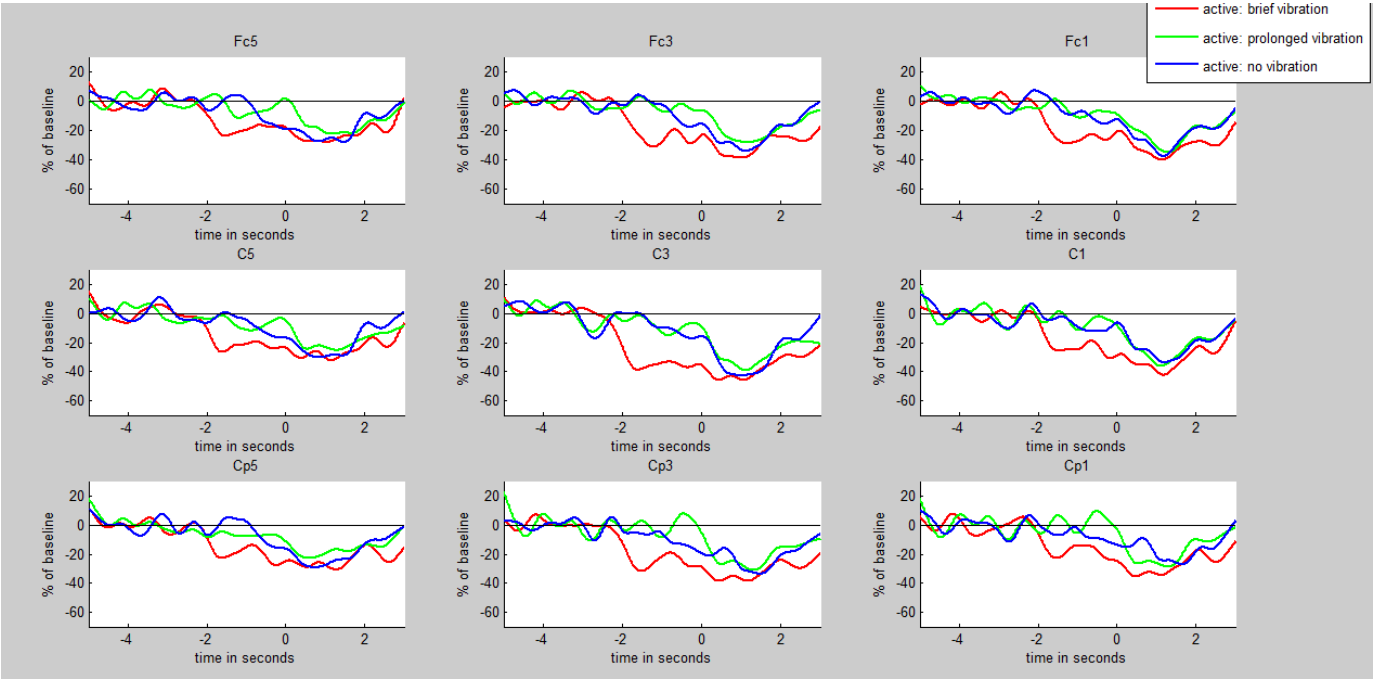

Figure 35: β-band power over the motor region of the left hemisphere. Active vibration is plotted in red, prolonged vibration data in green and the trials without vibration in blue. Brief tendon vibration leads to a decrease of power in the premovement period. (Vibration onset at -2 seconds)(Average over 5 subjects)

5.2 Alpha band

Concerning the α frequency band it is known that the lower parts of the band 7-10Hz shows response to almost any kind of task, while the upper alpha band 10-12 Hz is selective to the processing of sensory-semantic information. [4] In the case of this experiment a decrease in the α-band occurs with movement, but also prior to movement. Between the warning at -2 seconds and the actual movement, a slight increase of band power can be observed. Figure 36 displays the desynchronization of the alpha band in both active and passive conditions.

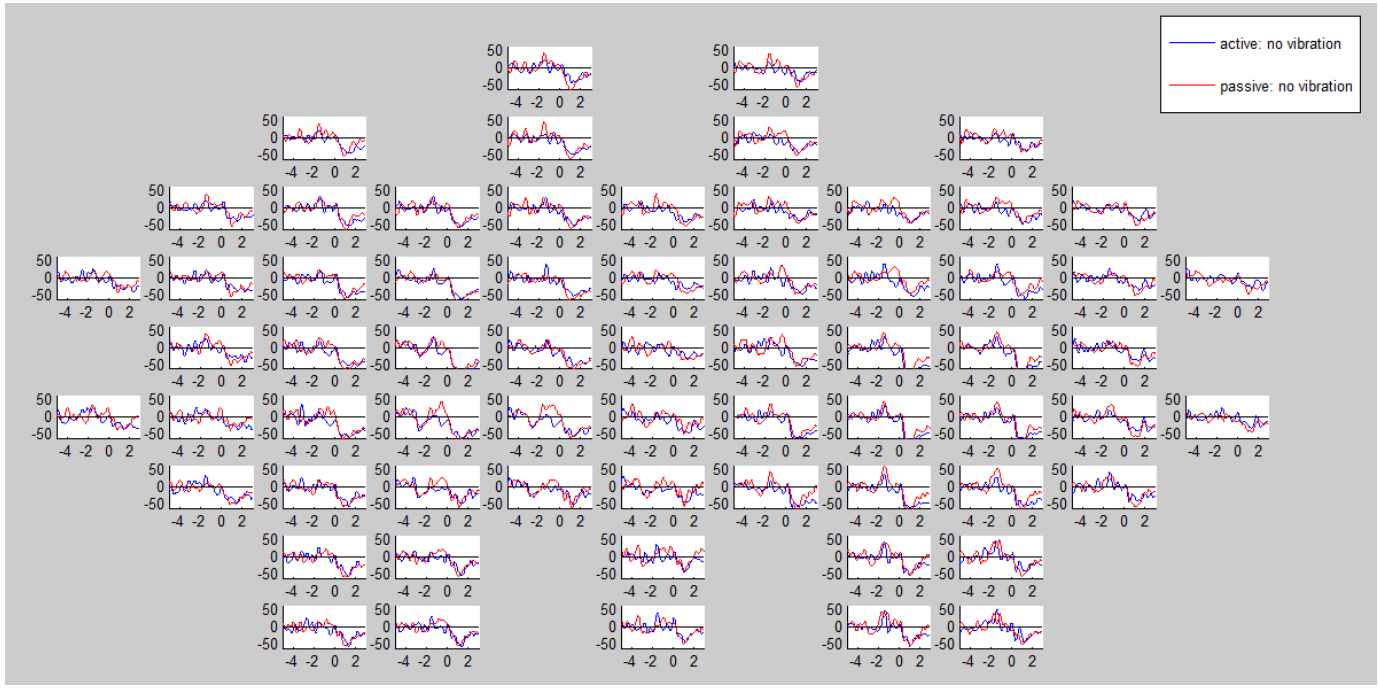

Figure 36: α-band power over all electrodes with no vibration applied: (active conditions:blue passive conditions:red). Power decrease can be observed during the movement. Electrodes over the left sensorimotor region also show power decrease around -2 seconds.

The effect of tendon vibration is much higher when focusing on the alpha bands. Figure 37 shows both active movement conditions with and without the application of brief tendon vibration. Especially over the left motor region, vibration leads to higher and longer-lasting decrease of band power prior to movement. Also the power during the movement is reduced. This leads to the assumption that the motor cortex is more active, when sensory feedback is augmented through vibration.

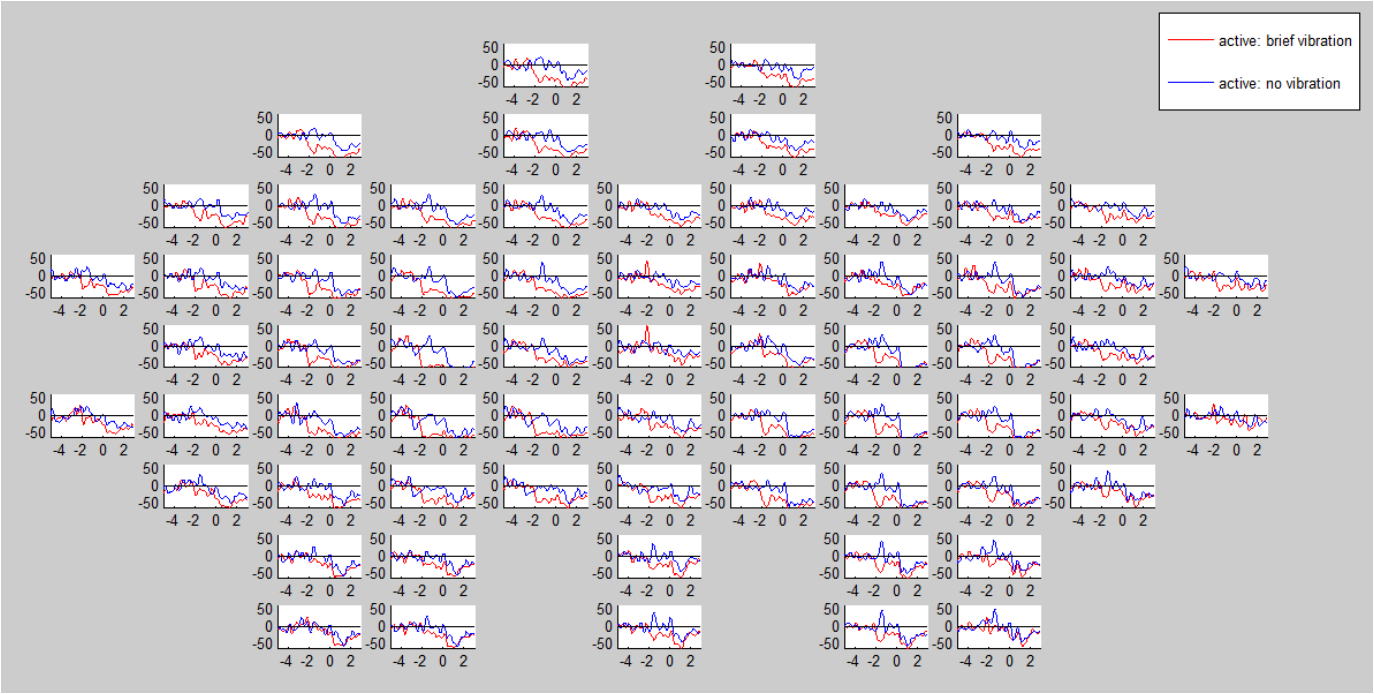

Figure 37: α-band power over all electrodes with- and without vibration applied: (no vibration: blue brief vibration: red). Power decrease can be observed during the movement. Electrodes over the left sensorimotor region also show power decrease around -2 seconds. This power decrease is much higher in cases with tendon vibration.

In the passive conditions this effect is even more prevalent. Instead of restoring after the warning signal, the power of the alpha band decreases and reaches the value of the active conditions. Figure 38 shows three conditions over the left sensorimotor region. The higher band power decrease due to vibration may in the active conditions lead to further decrease of the alpha band. This effect may be caused by simple addition of the two phenomena, even though some aspects may lead to the assumption that also movement intention plays a role in how far the alpha band power is decreased. Especially during the passive movement experiments, tendon vibration seems to prevent the motor cortex from resynchronizing between the warning and the movement cue.

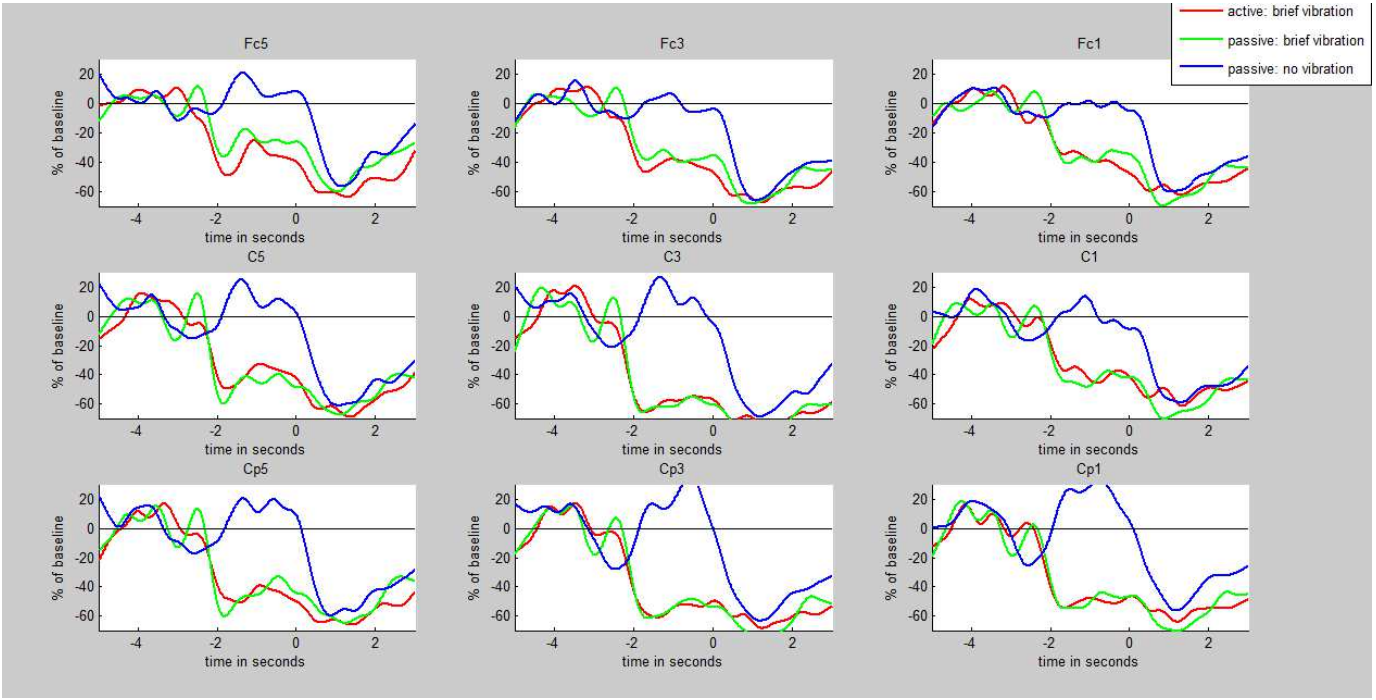

Figure 38: α-band power over the left motor cortex: Power decrease in the passive conditions is much more prevalent when tendon vibration is applied prior to the movement.

Prolonged tendon vibration was in prior expected to cause less desynchronization in the alpha band due to permanent stimulation of the muscle spindles. Even though after analyzing the data no significant difference between trials with prolonged vibration and trials without vibration could be found. An explanation for this may be a kind of fatigue reaction of the sensory cortex leading to the suppression of sensory inputs by the motor cortex after longer stimulation through vibration.

6 Discussion

During the four months at Marquette University, the previously described experiment was planned and executed based on the fundamentals given by several other studies that were realized at the INRL. This report reveals some of the problems that can occur especially during the phase of planning and piloting. EEG and especially new processing methods like ICA are tools for brain research that can lead to very impressive but also deceptive results. Therefore every conclusion has to be rethought carefully. The results explained in this report are therefore more of an overview, because most of the data collected is still not analyzed to its full extent.

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