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# EEG measurements to investigate the influence of music on brain activity while finger tapping

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**AFFIDAVIT**

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# Kurzfassung

## EEG Messungen um den Einfluss von Musik auf die Gehirnaktivität bei Fingertapping zu untersuchen

In dieser Arbeit wurde der Einfluss von Musik auf die Aktivität des Gehirns bei Bewegung, in diesem Fall Fingertapping, untersucht.

Probanden wurden beauftragt im Takt mit dem Finger zu drei verschiedenen Bedingungen zu tappen. Die ersten zwei Tappings erfolgten zu einfacher Musik mit isochronem Rhythmus mit zwei unterschiedlichen Frequenzen, bei der dritten Bedingung wählten die Probanden selbst eine Frequenz, welche sie ohne äußere Stimuli halten sollten.

Die Ergebnisse wurden einerseits topographisch als Plots dargestellt, welche die Desynchronisation der Bewegung an sich zeigen, die sichtbar im Alpha-Band ist. Andererseits wurden Zeit-Frequenz-Bilder analysiert, welche eine Interpretation der relativen Änderung des Signals innerhalb der Bewegung als Beta-Modulation erlauben.

Die topographischen Plots zeigen eine gut sichtbare Aktivierung der kontralateralen Areale der rechten Hand. In den Zeit-Frequenz-Plots ist die Synchronisation/Desynchronisation innerhalb der Bewegung in den meisten Probanden als Muster im Rhythmus erkennbar.

Obwohl kein signifikanter Unterschied zwischen den Bedingungen mit und ohne Musik erkennbar war, lieferte diese Studie dennoch interessante Einblicke. Durch weitere Untersuchungen könnte die Verwendung von Musik in der Rehabilitation erweitert und somit eine weitere Verbesserung von Leistung und Fortschritt erreicht werden.

**Schlüsselwörter**: Elektroenzephalogramm (EEG), Event Related Desynchronisation/Synchronisation (ERD/ERS), Neurorehabilitation, Musik, Fingertapping

# Abstract


## EEG measurements to investigate the influence of music on brain activity while finger tapping

In this study the influence of music on brain activity while moving, in this case finger tapping, was investigated.

Subjects were asked to tap their finger to three different conditions. The first two were tapping to simple music with an isochronous rhythm in two different frequencies. The third condition was to tap self-paced in a frequency the subject chose and should maintain without external stimuli.

The results were topographically displayed with maps, which display the desynchronization within the movement, visible in the alpha band. Besides that, time-frequency plots were analysed to allow an interpretation of the relative change of the signal within the movement as beta modulations.

Topographic plots show observable activation in the contralateral areas of the right hand. In the time-frequency plots the synchronization/desynchronization within the movement can be seen in most subjects as patterns in the according rhythm.

Although no significant difference was observable between the conditions with and without music, this study gave some interesting insights. By doing further investigations the usage of music in rehabilitation could be enhanced, leading to even better performance and progress results in patients.



**key words**: electroencephalogram (EEG), event related desynchronization/synchronisation (ERD/ERS), neurorehabilitation, music, finger tapping

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# Index of Abbreviations

B&B … Box and Block test

bpm … beats per minute

dB … Decibel

EEG … electroencephalogram

EPSP … excitatory postsynaptic potential

ERD/ERS … event related desynchronization/synchronization

FFT … fast Fourier transformation

fMRI … functional magnetic resonance imaging

IPSP … inhibitory postsynaptic potentials

MEG … Magnetoencephalography

MPA … movement phase-related amplitudes

PCA … Principal component Analysis

PMd … dorsal premotor area

Pre-SMA … pre-supplementary motor area

PSP … postsynaptic potential

ROI … region of interest

SMA … supplementary motor areas (SMA)

STG … superior temporal gyrus

# 1 Introduction

## 1.1 The electroencephalogram

The electroencephalogram (EEG) is a non-invasive method to measure the summed electrical brain activity on the scalp [1]. Oscillations of electric potentials are recorded with electrodes that are attached to the surface of the head. The number of electrodes can vary up to 256 per electrode cap. On one hand EEG offers a sufficient temporal resolution but on the other it only has a poor spatial resolution.

In the cortex pyramidal cell axons are aligned perpendicularly to the local cortical surface. The postsynaptic potentials (PSPs) generated by these cells can be measured as field potentials with an EEG. There are two types of PSPs, one constituting a depolarisation (excitatory postsynaptic potentials, EPSP), the other a hyperpolarisation (inhibitory postsynaptic potentials, IPSP) of the postsynaptic neuromembrane (Figure 1).

After an action potential has reached the presynaptic ending of the preceding excitatory neuron, cations flow into the nerve cell at the synaptic cleft causing an EPSP. The resulting potential gradient (depolarization) inside and outside along the neuronal membrane causes cations to flow towards the synaptic cleft in the extracellular space and away from it in the intracellular partition. Based on this mechanism the depolarization spreads throughout the cell. The other type of PSPs are the inhibitory postsynaptic potentials (IPSPs) which result in the opposite effect of the EPSPs and lead to an inversely directed ion flow. These ion fluxes play a significant role in generating field potentials.

In the human brain one neuron can have up to 10.000 synapses, which induce individual PSPs upon activation. Individual PSPs which are timely linked are summed up to a global PSP that can be measured on the scalp during an EEG. Since these signals are very weak they have to be amplified and processed to be analysed [31], [60].

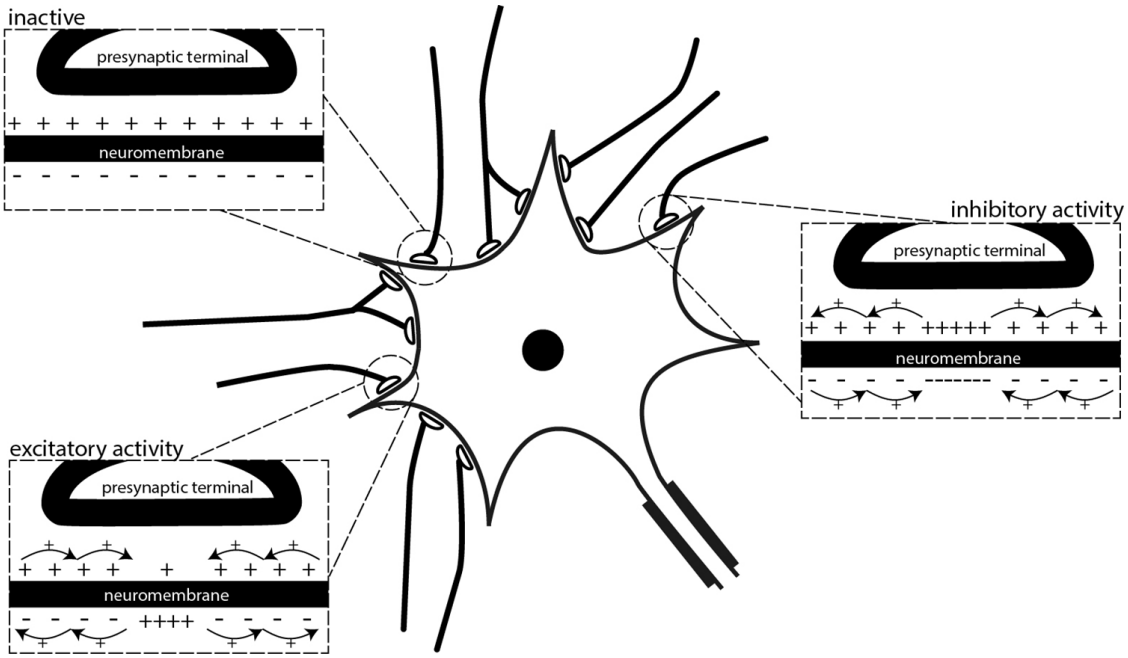


**Figure 1:** EPSP and IPSP explained by showing the ionic current flows along the neuronal membrane and the polarization of the sub- and postsynaptic membranes, indicated by arrows and + / - signs.

## 1.2 Brain activity while listening to a rhythm

Neuronal activity triggered by processing and playing music is distributed in certain areas of the brain, including the cortex, subcortex and cerebellum [36]. Studies reveal that listening to an auditory rhythm without moving shows similar brain activity patterns to actually moving to the sounds [15].

### 1.2.1 Listening to music reveals beta modulations

Fujioka et al. [15] plotted time-frequency maps of the right auditory cortex while listening to isochronous sounds and indicated that these maps display patterns that resemble the played rhythm.

EEG power change in the beta band is most likely correlated with motor functions [57]. The beta frequency band (14-30 Hz) [31] depicted in Figure 2 shows a decreased activity immediately after the stimulus onset. This event-related desynchronization (ERD) reaches its minimum with latency of around 200ms after the stimulus presentation. The following event

related synchronization (ERS) has its peak around the time of the next auditory onset. Hence a periodic auditory stimulation provides a periodic ERD/ERS pattern in the neuromagnetic beta oscillation.

Predictive movement planning may be enhanced by the beta rebound before the next auditory stimulus which seems to encode an internal depiction of the predictable time interval [15].

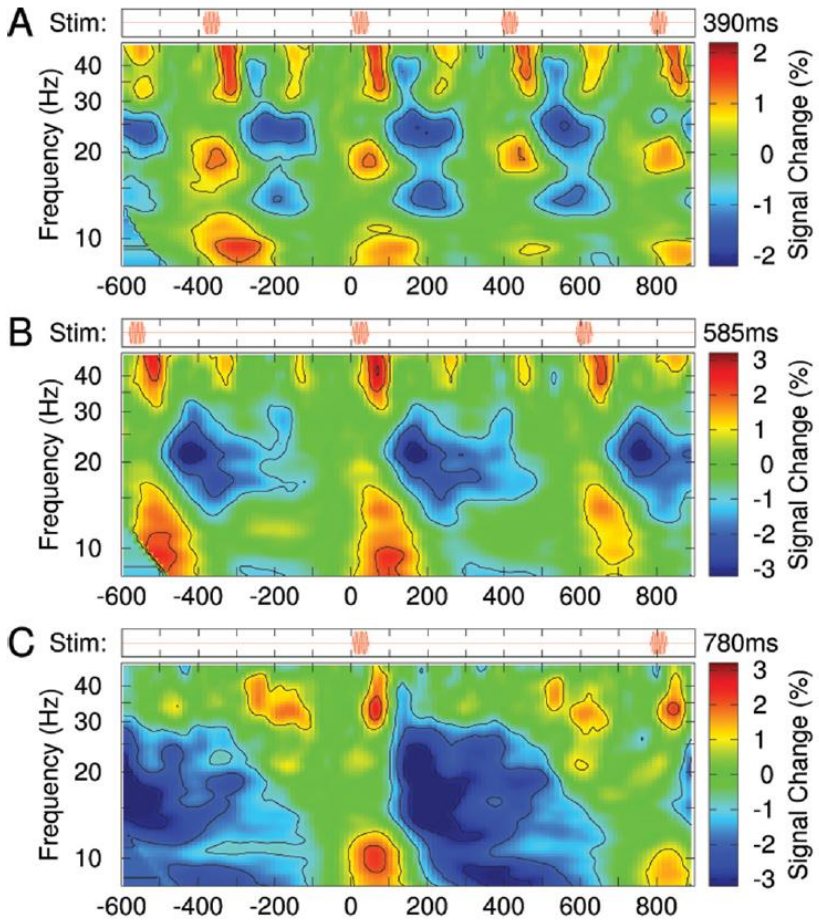


**Figure 2:** Time-frequency maps of the right auditory cortex. The neuronal activity shows a periodic pattern of ERD and ERS. The auditory stimulus was set every (A) 390ms, (B) 585ms, (C) 780ms. (Modified from [15])

### 1.2.2 Activated brain areas

Both auditory and motor systems are activated when listening to an auditory rhythm without moving to it [15]. Included areas are

- premotor cortex, which projects directly to the spinal cord
- supplementary motor areas (SMA) and pre-supplementary motor area (pre-SMA)
- basal ganglia
- cerebellum

These areas are activated during tasks including timing, perception of duration and rhythm but also during motoric tasks [16].

Besides the fact that hearing rhythm activates motor areas of the brain, external rhythmic cueing also leads to rapid motor synchronization regardless whether there is a neurological disability or not [55]. After finding first evidence for auditory-motor synchronization, investigations of the auditory-motor pathway were started, focussing on the reticulospinal connections, cerebellum, brainstem and the basal ganglia [43], [54]. These studies found areas of the neocortex, basal ganglia, cerebellum and thalamus to be responsible for processing time information [21], [56].

In a study conducted by Grahn and Brett subjects had to try to remember different kinds of rhythms only by listening [16]. Figure 3 shows the functional magnetic resonance imaging (fMRI) results of the random effects analysis of activity patterns while memorizing the rhythms compared to those measured at rest (all groups and conditions).

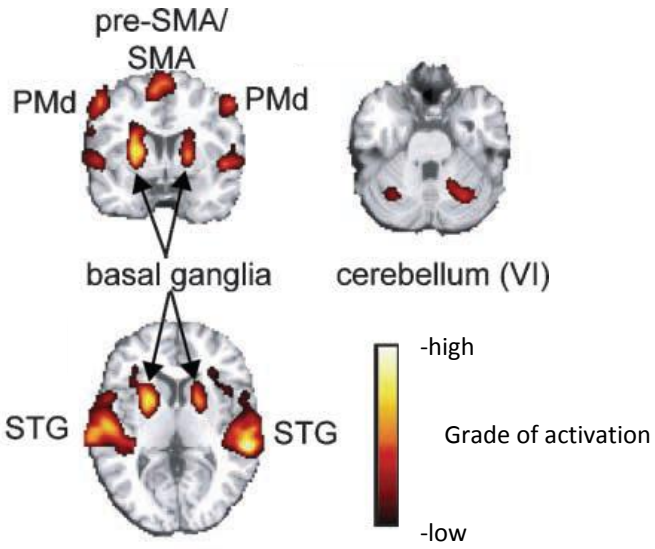


**Figure 3:** Activation patterns for all conditions versus rest, defining the functional regions of interest (ROIs). PMd = dorsal premotor area; SMA = supplementary motor area; STG = superior temporal gyrus; VI = cerebellar crus VI. (Modified from [16])

The pattern shows that while perceiving rhythms a bilateral network of motor areas is activated, even when no movement is made. Comparing listening to the rhythms to resting, bilateral activation was observed in areas including the pre-SMA/SMA, basal ganglia, PMd, cerebellum, and superior temporal gyri. The fact that participants were instructed not to move any part of their body during the test might explain the lack of activation in primary motor cortex. Therefore the results are likely to show activation as a reaction to only perceiving rhythm [16], [35], [45].

The cerebellum as well as premotor areas may be necessary for basic timing processes where they encode the time intervals in the first place. This information is then most likely detected and related to an isochronous beat interval by the basal ganglia and pre-SMA/SMA [16].

SMA and basal ganglia are involved in predictable, internally generated movements [9], [12], [15]. Hereby, the basal ganglia control motoric activities and suppress unwanted movement [49].

## 1.3 Moving to a rhythm

The fact that rhythm affects the total movement pattern rather than only the timing of movement was shown by studies of gait parameters with neurologically injured people. Synchronizing movement to music occurs in most people without formal training [4].

### 1.3.1 Moving to rhythm as a congenital effect

At the age of 5 months infants begin to move spontaneously as a response to music [4].
A regular beat might be extracted from incoming temporal stimuli by certain motor areas. The fact that these motor areas are involved in beat processing is supported by studies revealing a direct link between movement and beat perception in infants. In one study by Phillips-Silver and Trainor babies were trained by letting them listen to a repetition of a rhythmic pattern without accented beats. Subsequently, the infants were divided into two groups: one group was bounced on every second beat, the other group on every third beat. After being trained in the respective manner babies chose to listen longer to the auditory test stimulus with accented beats coinciding with the beats to which they were bounced in the training phase [9], [12], [40].

### 1.3.2 Moving to rhythm as an unconscious effect

Frequency modulations can unknowingly be detected [28]. Extracting time information from sensory stimuli makes them available for the motor output without cerebellar processing.
This finding indicates that there is a possibility of directly influencing the motor effectors either in the cortex or at spinal levels to induce motor entrainment to rhythmic auditory stimuli.

The auditory nerve can directly compute timing information by neural excitation patterns that provide a precise physiological coding. This coding allows synchronization between auditory stimulus and motor response by transferring directly into adjacent motor structures and therefore dragging along neural motor codes. The facts that this processing is very fast

and that patients suffering from cerebellar damage show good performances suggests that specially dedicated "ring circuitries", like e.g. the cerebellum and/or the basal ganglia, are not included in the processing of motor entrainment [5], [6], [51].

However, the peripheral processing theory and the central mechanism hypothesis do not exclude each other, since the core timing functions are located in the basal ganglia or cerebellum [18], [23]. When conscious processing of temporal information is required, those two regions show specific activation, presumably at different stages of processing [41].

### 1.3.3 Tapping to a beat

While tapping to a metronome the motor system can adjust to a predictable pace. Within two or three auditory rhythmic cues the stability of motor control shows a significant increase [20]. This happens by programming a movement sequence in advance which produces an internal rhythm that is loosely matching the external pacing. This isochronous tapping sequence might be additionally controlled in a closed-loop manner, which relates the external visual or acoustic stimuli with the fingers' feedback to evaluate how far or if the precise timing of the tapping sequence has been achieved.

The tapping involves neural circuits associated with time and rhythmic processing. Also a complex circuit is specifically active which involves cortical areas, cerebellum, and basal ganglia [28].

### 1.3.4 Different activation patterns in musicians and non-musicians confirms an automated process

Molinari et al. [28] asked subjects – musicians and non-musicians – to rhythmically tap the finger to an acoustic stimulus. Functional neuroimaging tests showed activations in both groups in the same areas of the brain. The difference between non-musicians and musicians was the degree of activation in these structures. Non-musicians had a greater activation of cortical areas, whereas musicians, which are generally conscious of rhythmic patterns and

structures, showed a greater cerebellar activation. The activation pattern of non-musicians suggests a highly automated sensorimotor process for rhythmic tapping.

Human bodies can react to rhythmic variations without any obvious perception. This leads to the idea that listeners might be affected by components of a piece of music that are not obviously and consciously detectable.

In conclusion, the data shows that timing is a distributed function involving different neural circuits that are capable of processing time information. According to the specific timing requirements of a given task their activation and role can vary [28].

## 1.4 Usage in therapy

In patients with brain damage for example, music may play an important role in recovery. Depending on the degree of damage and the disease involved, the time of rehabilitation can be very long and frustrating for the patient. Recent studies to be discussed in this section have shown that including music based therapies in rehabilitation programs are able to improve the performance and progress of the patients.

### 1.4.1 Rhythmic cueing as a part of rehabilitation

Since rhythm is the organizing factor in music, it plays a major role in therapeutic applications for motor rehabilitation. It hereby serves as a timekeeper but is also essential for the auditory-motor synchronization. For people's gross motor rehabilitation auditory rhythmic cueing is used as an effective tool [3].

The two primary factors that help to achieve good rehabilitation results by using auditory rhythms are:

1) rhythmic synchronization and
2) the fact that the cortical plasticity can be facilitated by systematically using rhythmic cueing. It is also promoting structural and functional connectivity in the brain [17].

Interaction between auditory rhythm and motor responses can be used for rehabilitation in movement disorders [55]. Rhythmic synchronization is an effective tool for gait rehabilitation of patients with diseases like Parkinson's disease, traumatic brain injury, spinal cord injury and stroke [20], [26], [42].

### 1.4.2 Factors influencing muscular movement control by music

Thaut [53] developed a clinical motor rehabilitation model which is based on auditory-motor research. Some facilitating factors for muscular control of movement patterns to rhythmic cues within this model are:

1) Smaller muscular fatigue

2) Predictability of stimuli enhances automatized movement performance

3) Response quality and reaction time is improved by enhanced response anticipation

These are only some factors that have been integrated into neurologic music therapy techniques to work on range of motion, muscle control and coordination, muscle strength and endurance, motor planning, and functional motor skills [52].

### 1.4.3 Showing the positive influence of music on rehabilitation based on an example

Friedmann et al. [14] did rehabilitation experiments including an instrumented, sensorized glove ("*MusicGlove*"), which was developed for this study. The experiment is based on a music video game similar to "Guitar Hero" (Figure 4) and used it to improve grasping movements of patients.

Adding music to therapy is due to its motivating, repetitive and sensory-rich features a promising application. After suffering from stroke, music can induce plastic changes in the motor cortex, thereby increasing cognitive functioning and well-being, attention span, and neuropsychological scores.

The three therapies tested in this study were the above mentioned MusicGlove, an isometric grip training of a stationary object ("*IsoTrainer*") and the conventional tabletop hand exercise assisted by rehabilitation therapist. The therapy with the MusicGlove involved speed and dexterity units. The results were shown at the end of each song as a percentage of correctly hit notes.

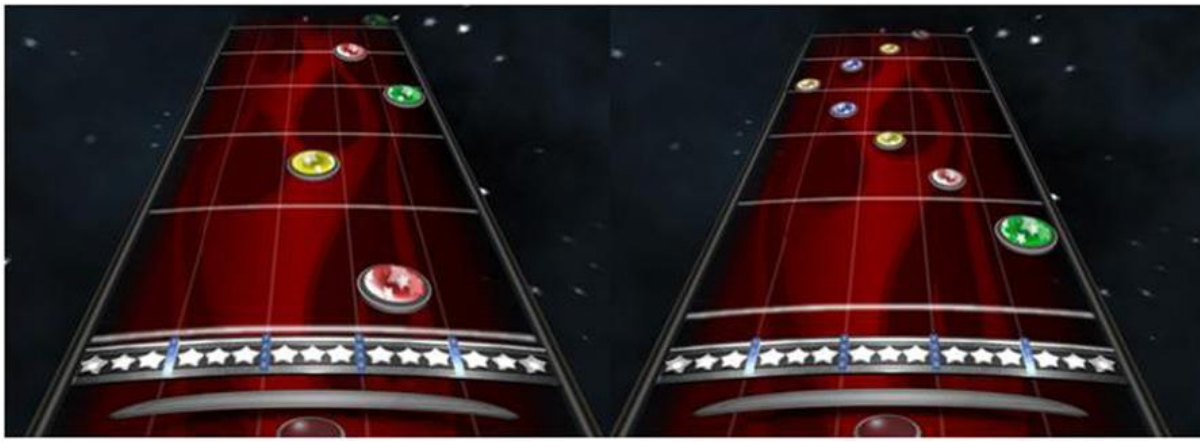

**Figure 4:** Screenshot of the rehabilitation game using MusicGlove. Each training session began and ended with the folloing two assessments: For the dexterity test (left) notes are randomly appearing on frets 1-3, different to the speed test (right) where notes appear in a sorted sequence on frets 1-5. In both tests the frequency of appearing notes increases with time. (Modified from [14])

The results showed that the subjects improved their Box and Block (B&B) score [24] pre to post-training with the MusicGlove, although an improvement of only 3 points is a rather small effect (Figure 5). The B&B test evaluates how many blocks can be picked up and placed in a box in a time period of 60 seconds. There was a significant linear relationship between the percentage of total notes hit during the assessment scores and B&B scores. Related to grasping small objects, the results showed that there was a significant improvement in the hand function. Furthermore the improvement of fine gripping functions lead to qualitative, self-reported functional gains such as double-clicking a mouse, tying shoes, washing dishes and independently using the restroom.

A huge advantage is also that the participants were highly satisfied with the MusicGlove and it was the most motivating method. Also the musical aspect of the therapy was very important for both the MusicGlove and IsoTrainer. Eleven out of 12 (92%) participants preferred MusicGlove over the other kinds of therapies.

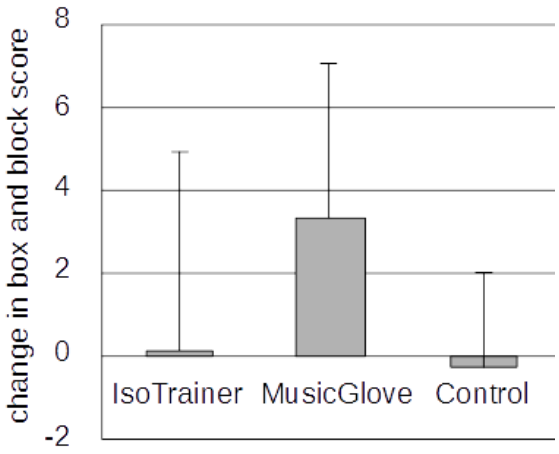


**Figure 5:** This plot shows the results for the improvement in hand function after a training period of two weeks with the MusicGlove, evaluated by the "Box and Block" score (modified from [14]).

In summary, it can be stated that including music in rehabilitation shows improved results for movement as well as the mood and motivation of patient. Taken together the usage of the MusicGlove gave rise to a greater compliance of the patients in combination with better clinical outcomes.

## 1.5 Motivation

### 1.5.1 Music facilitates movement

It is known that music improves and facilitates movement as described above (1.3 Moving to rhythm). As a historical example work songs support people while doing their hard work; march music and wandering songs animate people to move almost automatically [2], [58]. Simply listening to an isochronous auditory rhythm shows a modulation in the auditory and motor systems, revealing a connection between these two systems [15]. Besides that, an activation of the mesolimbic system, the region of the brain which is involved in reward processing, is observed [25].

Using music in rehabilitation also showed high motivation of the patients [14].

### 1.5.2 Goal

As mentioned several studies showed that music has a significant influence on movement. This work aims to elucidate the direct influence of music on the brain by comparing finger tapping to music to self-paced finger tapping. EEG measurements in these two experimental settings might show different activation patterns in certain areas of the brain which will be displayed by ERD/ERS maps. The scientific insights in this study can be used as a basis to improve therapy for neurological diseases and shorten the duration of therapy.

### 1.5.3 Hypothesis

Listening to an isochronous rhythm activates the motor cortex as mentioned above [15]. Therefore tapping to music with an isochronous rhythm might lead to a stronger activation in the EEG of certain areas of the motor cortex, leading to an ERD in alpha or beta band. As depicted in Figure 6 the C3 region is the contralateral corresponding area to movement of the right hand, hence this region will presumably show the greatest differences [38]. The influence of music might also be seen in the activation of bigger areas in the motor cortex when comparing tapping to music and self-paced tapping, since a difference in activation patterns in musicians and non-musicians while tapping to music was previously observed [28].

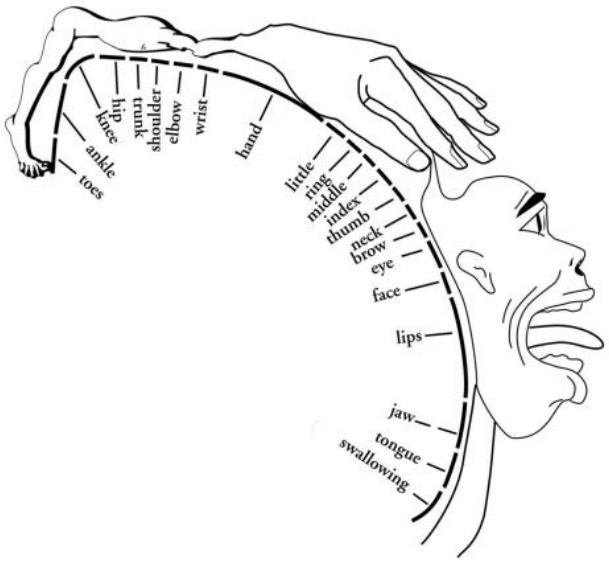


**Figure 6:** Homunculus according to the motor strip of the brain. (Based on Penfield's classic diagram [34])

# 2 Methods

In this chapter the used methods to perform the required experiments are described. The experimental setup including the paradigm and electrode positions but also the signal processing including artefact removal and data visualization will be explained.

## 2.1 Architecture and design

### 2.1.1 Subjects

The EEG of 11 healthy and right handed individuals (8 male and 3 female) was measured. The mean age was 25,2 ± 1,7 years (SD). The handedness was confirmed based on a standardized test [32].

### 2.1.2 Setup

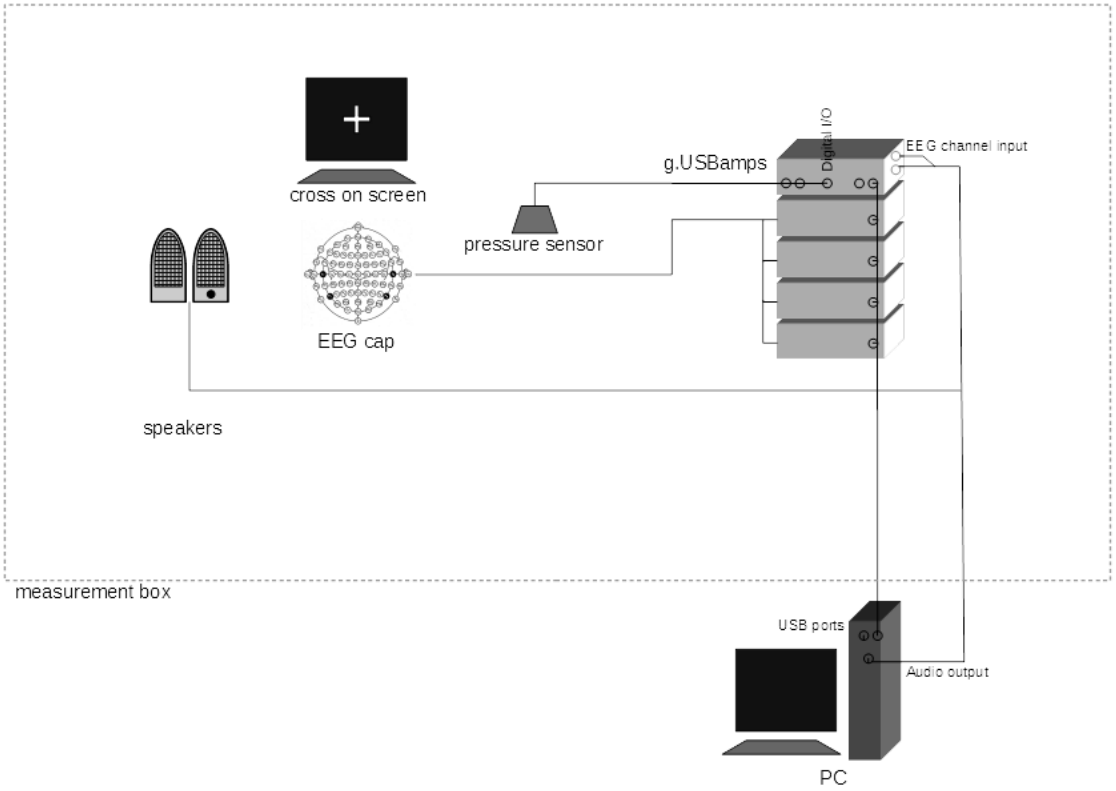


**Figure 7:** Experimental setup for all conditions showing the computer outside and the EEG setup, speakers, pressure sensor and another screen inside the electrical shielded measurement box.

In the experimental setup as depicted in Figure 7 audio stimuli were presented through speakers to the subject sitting in the electrical shielded measurement box. Each subject was asked to sit as still as possible and avoid any additional muscle activity to reduce artefacts. The actual finger tapping to music and self-paced finger tapping was recorded with a pressure sensor positioned below the finger. This sensor was connected to the digital input of one amplifier (g.USBamp, g.tec, Austria) of the five 16 channel amplifiers that were combined. The subject was told to tap to the music in the accurate beat frequency in an even and smooth movement. The finger tap could then easily be determined by edge detection, since the pressure sensor records a signal switching between 5 V and 0 V upon activation.

To synchronize the finger tap with the actual audio onset, the audio output of the computer was connected via two modified EEG electrodes to one EEG channel input of one g.USBamp.

## 2.2 Experimental paradigm

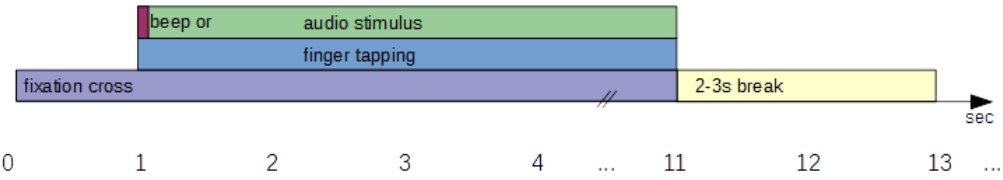


**Figure 8:** Paradigm for the EEG measurements. The finger tapping is either performed to an audio file or self-paced after a beep, each starting at second 1.

The EEG and finger tapping was recorded under three conditions. One second before the actual tapping started, a fixation cross was displayed on the screen in front of the subject and remained until the end of the tapping time. The finger tapping was recorded for 10 seconds. A break with a randomized length (2-3 seconds) was the last part of the trial (Figure 8).

The three conditions for the tapping were:

1. Self-paced: without any music. A start beep was played at the beginning to introduce the start of the tapping time.
2. An audio file ("synthetic melody") was played with 1.5 Hz (40 beats per minute [bpm]): an easy melody in a synthetic sound with an isochronous rhythm.
3. An audio file ("synthetic melody") was played with 0.66 Hz (90 bpm): same as for condition 2.

Three runs were recorded for each condition. Each trial was repeated 22 times per run which resulted in a total number of 66 trials per condition. Additionally, before the first run a rest period was recorded for 3 minutes. The subject was told not to tap or move at all and no music was played.

The 11 subjects were divided into two groups as shown in Table 1.

**Table 1**: The order of conditions is shown for each group and session.

| | **Group A** | **Group B** |
|---|---|---|
| **Session 1** | Rest | Rest |
| | "Synthetic melody" 90 bpm | Self-paced |
| | "Synthetic melody" 40 bpm | "Synthetic melody" 90 bpm |
| | Self-paced | "Synthetic melody" 40 bpm |
| **Session 2** | "Synthetic melody" 90 bpm | Self-paced |
| | "Synthetic melody" 40 bpm | "Synthetic melody" 90 bpm |
| | Self-paced | "Synthetic melody" 40 bpm |
| **Session 3** | "Synthetic melody" 90 bpm | Self-paced |
| | "Synthetic melody" 40 bpm | "Synthetic melody" 90 bpm |
| | Self-paced | "Synthetic melody" 40 bpm |

By mixing up the order of the conditions between groups A and B, assumptions that previously listening and tapping to some music may influence the self-paced part could be eliminated.

## 2.3 Choice of music

In a pre-study the most suitable audio file was chosen out of 6 different versions, each in two different beat frequencies (0.66 Hz, 1.5 Hz) with an isochronous rhythm.

The audio files were:

- only melody, natural piano sound ("*natural melody*")
- the same melody accompanied by chords, natural piano sound ("*natural chords*")
- only melody, synthetic sound (similar to the background music of the game "Super Mario", "*synthetic melody*")
- the same melody accompanied by chords, synthetic sound ("*synthetic chords*")
- isochronous metronome beat click ("*metronome click*") and
- isochronous metronome beat in sense of repeating one chord in the beat ("*metronome chords*")

All audio files were generated with the iPad App “GarageBand” (Apple, Cupertino California, USA) to easily modify the beat frequency, prevent individual inaccuracy while playing the piano, avoid modifying length, ensure exact timing of the notes and prevent background noises when recording. The finger tapping was recorded with the pressure sensor and could then easily be determined by edge detection, since the pressure sensor records a signal switching between 5 V and 0 V upon activation.

The accuracy of the finger tapping compared to the actual audio onset was evaluated to come to a decision. Additionally the subjects were asked to fill out 3 questionnaires where they had to state whether an audio file facilitates the tapping or not according to their personal opinion. Based on this data a simple ranking system was applied which indicated “synthetic melody” as the most suitable audio file.

## 2.4 EEG measurement

### 2.4.1 Electrodes

Fifty-nine passive Ag/AgCl electrodes were positioned in a symmetric order over the sensorimotor area according to the 5% international 10/20-system (Figure 9) [33]. Thirty-one of these 59 channels have four orthogonal neighbours according to the plan (Figure 9), which were used for further calculations.

On the left and right mastoid reference and ground electrodes were placed, respectively. Not to change its potential during the recording, the reference electrode is supposed to be electrically neutral [22]. Electrode impedances were measured to be lower than 5 kΩ.

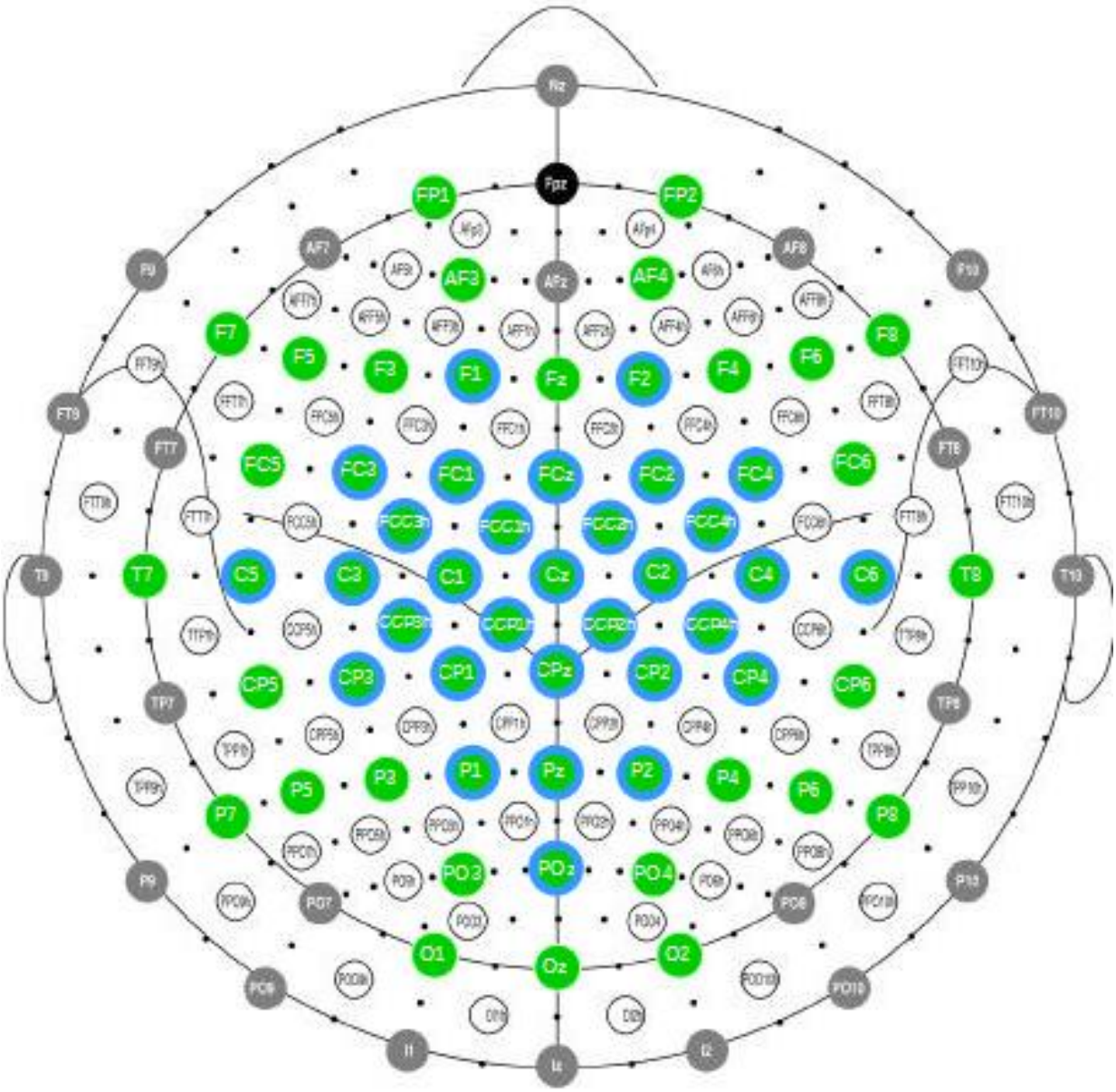


**Figure 9:** Electrode positions for the 59 EEG electrodes that were measured are displayed in green. The blue framed electrodes are the ones that were used for calculations. (Acquired from [33])

## 2.5 Implementation and detailed design decisions

### 2.5.1 Software

For obtaining and processing signals Matlab® and Simulink® (MathWorks Inc., Natick, USA) were used. For presenting the paradigm Ruby (Yukihiro Matsumoto et al., *http://rubygame.org/*) was included. The data was saved in the "General Data Format" (".gdf") [44].

### 2.5.2 Signal acquisition

#### 2.5.2.1 Settings for the EEG measurement

The sampling rate for the experiments was set to 512 Hz. The raw EEG data was band pass filtered with a Chebyshev filter of $8^{th}$ order between 0.1 and 200 Hz. A notch filter at 50 Hz was applied.

#### 2.5.2.2 Artefact removal

The variance of the EEG channels for each subject and every run was calculated. To eliminate broken channels the median of the variance for each run was computed. A threshold of ten times the median of this variance was set. Every channel that had a value above this threshold was set as an outlier and ignored for further calculations.
Figure 10 shows the example of one subject. The variance median threshold was calculated and is shown as a horizontal line at around 2000 $\mu V^2$. Channel 1 and 2 are above the threshold and therefore removed. Figure 11 displays that the variances after removal have a smaller distribution.

To eliminate prominent artefacts Principal Component Analysis (PCA) was applied. After calculating eigenvalues, the first two of those were removed, because these cover mainly eye blinking and noise resulting in significantly higher values than the following eigenvalues. The back transformation was performed considering the previously erased channels. The mean variance after this procedure was significantly smaller (Figure 12).

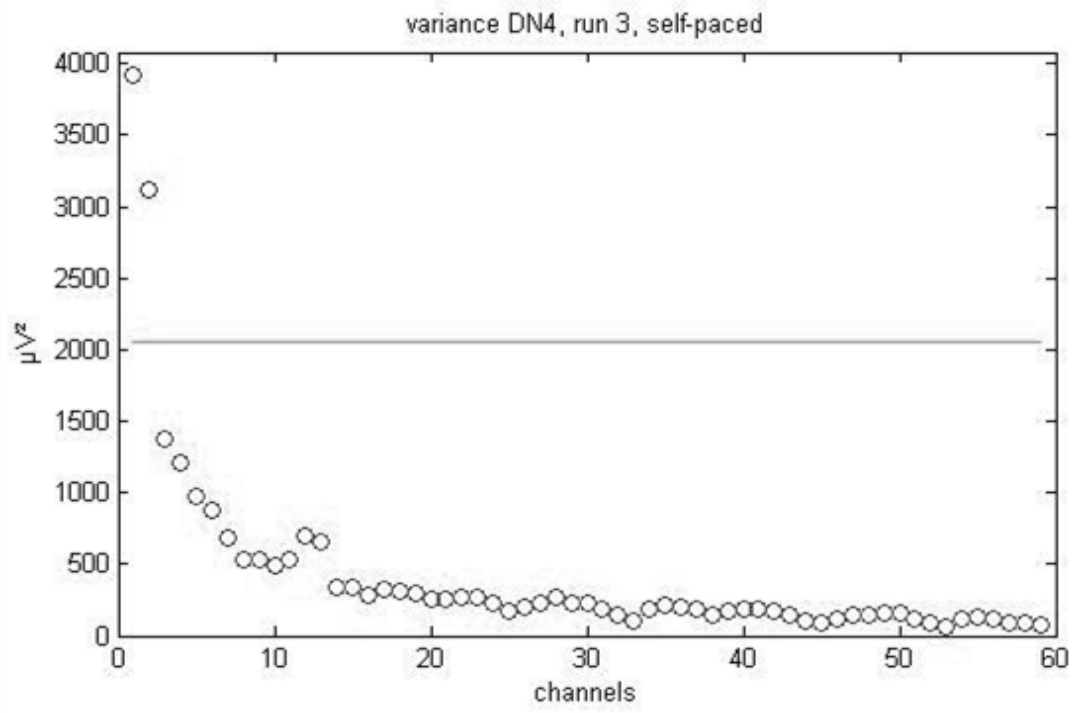


**Figure 10:** Channel variances for subject DN4, run 3, condition self-paced. The first two channels are higher than the threshold which is displayed as a horizontal line at 2050µV² and was calculated by determining the median of the variance times 10.

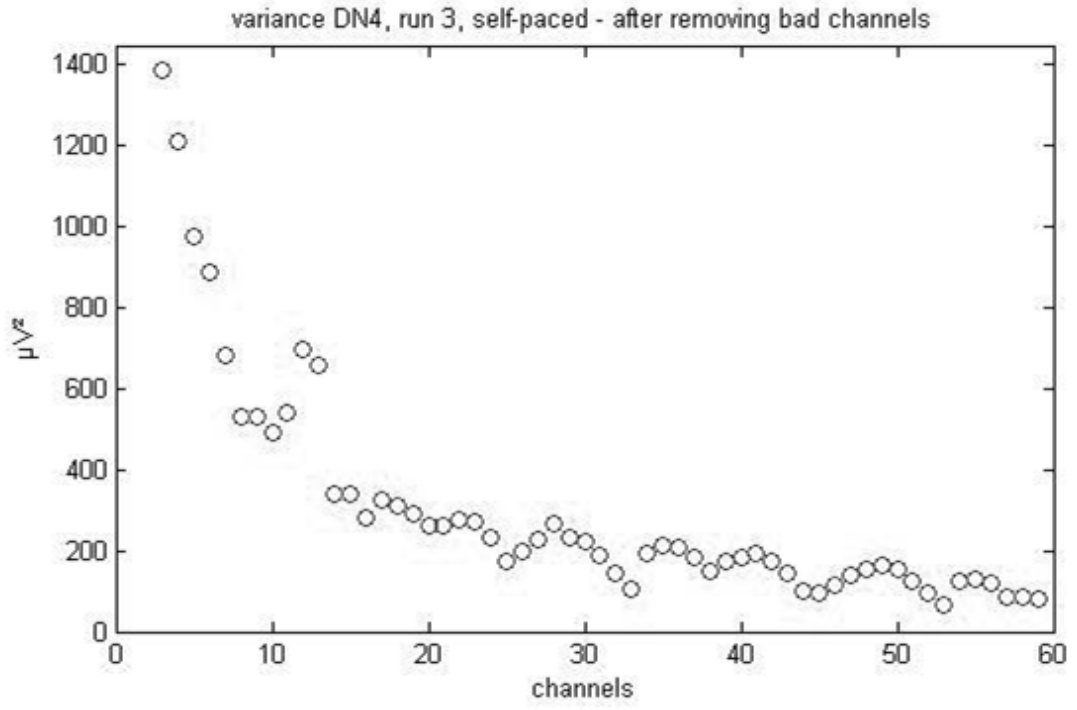


**Figure 11:** Channel variance for the same subject DN4, run 3, condition self-paced, after removing bad channels. No outliers can be seen.

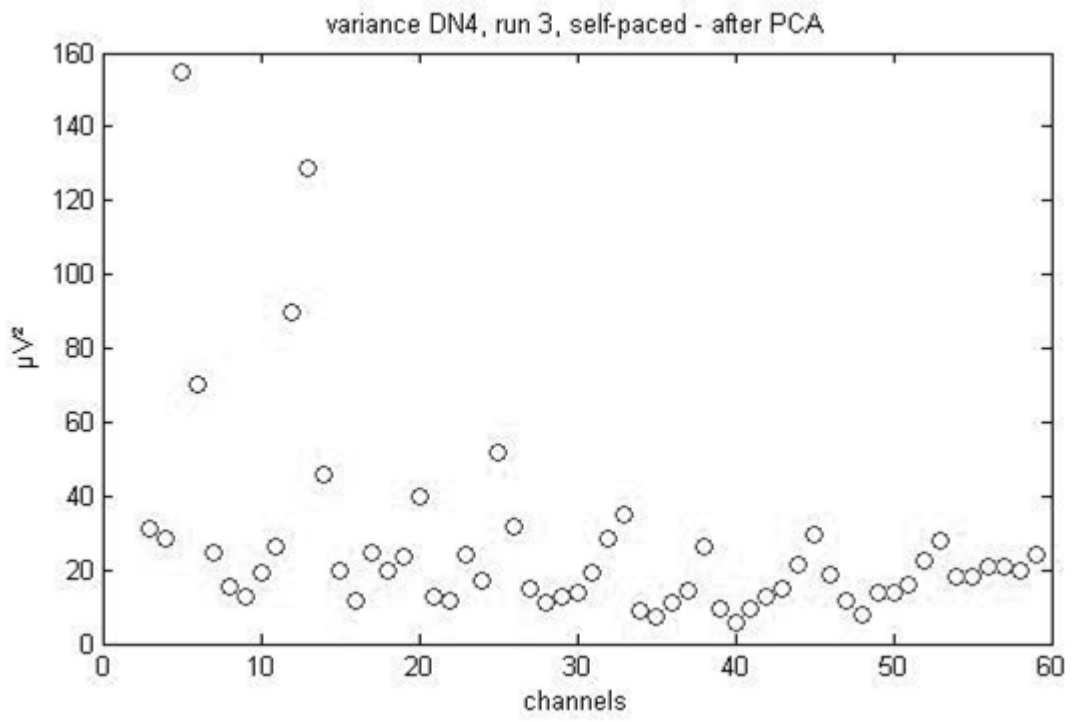


**Figure 12:** Channel variance for the same subject DN4, run 3, condition self-paced, after artefact removal with PCA and back transformation.

### 2.5.3 Interpolating missing electrodes and calculating power spectrum

Laplacian derivations were chosen as a re-reference method, which is necessary since a common reference electrode was used [22], [38]. Laplace value for one electrode ($chan_{lapl}$) was calculated by subtracting the mean of the four orthogonal channels ($chan_{surr}$) of the centre channel ($chan_{center}$).

$$chan_{lapl} = chan_{center} - \frac{1}{4}\sum_{i=1}^{4} chan_{surr,i} \quad (1)$$

After removing the "bad channels" some channels were missing to apply the Laplacian method. In this example depicted in Figure 13 the Laplacian value of FC1 had to be calculated. The four surrounding electrodes were F1, FC3, FCz and C1. Therefore the Laplacian formula would be:

$$FC1_{lapl} = FC1 - \frac{(F1+FCz+C1+FC3)}{4} \quad (2)$$

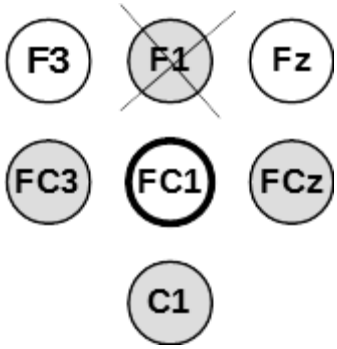


**Figure 13:** An example for calculating laplacian values, in this case for FC1 where the surrounding electrodes are F1, FC3, FCz, C1 and F1 is missing.

F1 had been removed due to exceedance of the threshold for variance. The mean values of the two surrounding channels F3 and Fz were calculated to interpolate F1, which leads to a new formula (equation (3)). If one or both of the channels for interpolation were missing the center electrode – in this case FC1 – was set to NaN.

$$FC1_{lapl\_interpolated} = FC1 - \frac{(\frac{(F3 + Fz)}{2} + FCz + C1 + FC3)}{4} \quad (3)$$

The Laplace values were then used to calculate the power spectrum using Welch's method [59]. The EEG data was divided into Hamming windows with a length of 1024 samples, which is a time of 2 s, leading to a frequency resolution of 0.5 Hz. The windows had a 50% overlap and a fast Fourier transformation (FFT) was applied to each of them. These results were averaged over the windows and afterwards averaged over all trials for each condition. Subsequently, these results were averaged over runs, and movement against rest condition was plotted individually.

### 2.5.4 Topographic visualization of sustained amplitude modulations

The Brainstorm toolbox [43, *http://neuroimage.usc.edu/brainstorm*] is a MATLAB based, open-source application to process and display EEG and Magnetoencephalography (MEG) data. The graphic interface allows topographic visualization to display the desynchronization of the movement itself.

The μ-rhythm is similar to the alpha rhythm regarding frequency and amplitude, but is observable over the motor cortex. It is detectable when the body is at rest. Performing motor actions like in this case finger tapping, lead to a desynchronization of the neuronal populations being in synchrony and can be visualized as alpha desynchronization in Brainstorm.

The amplification in decibel (dB) of the relation between activity to rest was calculated for the power spectrum from 0 up to 50 Hz for all 31 channels for each subject according to equation (4). In this work rest was separately recorded for 3 minutes at the beginning of each experiment.

$$ERD/ERS_{dB} = 10 * log10\left(\frac{A}{R}\right) \quad (4)$$

An averaging interval between 8.5 and 12 Hz was chosen to determine the activity according to the alpha section. Although the alpha band reaches from 8 to 13 Hz [31] a slightly smaller interval was used since the peak at the lowest relevant frequency was at 8.5 Hz and the highest at 12 Hz for all subjects and channels. The computed results were displayed with brainstorm.

### 2.5.5 Time-frequency-plots of movement phase-related data

Time-frequency plots represent a signal over both, time and frequency. It displays dynamic amplitude modulations within the movement itself. Those modulations can be seen in the beta band as relative changes of the signal over time.

The subjects were told to tap the finger in the rhythm that was heard, so the time of the lowest position of the index finger, which is when the audio stimulus was heard, is the time the pressor sensor was touched and hereafter called tapping time (Figure 14).

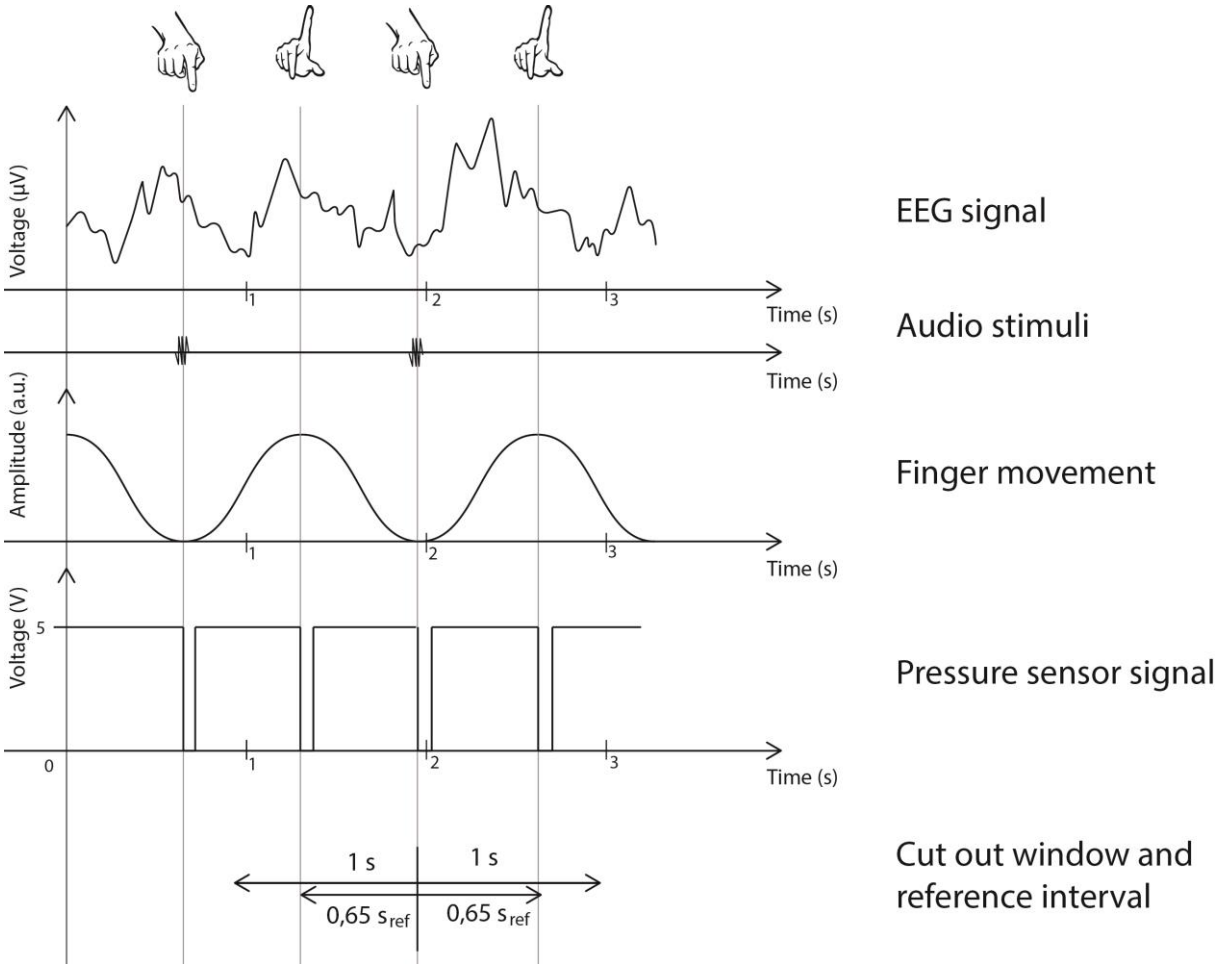


**Figure 14:** Sketch to explain the relationship between audio stimuli, finger movement and the therefore resulting signal at the pressure sensor, and the cut out window of (-1; 0; 1) s and the reference interval of (-0,65; 0; 0.65) s with time zero being the actual time of the finger tap.

The EEG data of all trials were stringed together. Regarding the finger tapping times a time interval from -1 to 0 s before and from 0 to 1 s after the actual tapping time was cut out of the EEG signal (Figure 14). The reference interval in this segment was set from -0.65 to 0 before and from 0 to 0.65 s after the interval (Figure 14). The time of 0.65 s was chosen because it is half the time between two taps of the slow melody. These cut out windows were averaged, then the bandpower was calculated with a bandwidth of 2 Hz. These results were displayed in Matlab with a 3-D shaded surface plot ("`surf`") to get time-frequency-plots for each subject.

To interpret a group study the values after calculating the bandpower for all subjects were averaged and displayed.

The time-frequency plots were calculated for the fast and the slow melody. For the self-paced tapping time-frequency plots were not possible to compute, due to the lack of consistency in the frequency of the tapping. The subjects tapped in a rhythm that was freely chosen and varied from run to run since there was no indicated instruction of tapping frequency.

### 2.5.6 Calculating significance of amplitude modulations

To determine whether or not there is a significance between the three conditions – slow music, fast music and self-paced – each condition was compared to the other two. Since the frequency of the μ-band is variable from subject to subject the values were determined manually [38]. In the power spectrum the highest peak was sought in the alpha range for each subject. At this exact frequency the amplification in decibel of the relation between activity to rest was calculated again. The rest period was recorded at the beginning of the experiment for 3 minutes. Friedman's test was then applied on the three vectors containing the amplitude modulations in dB of the specific frequency for each condition. This test sorts values within data sets and adds up the rank sums. The bigger the differences between the rank sums of the samples are, the lower is the resulting p-value which indicates the statistical significance [13].

# 3 Results

This chapter presents the power spectral density, topographic visualization, time-frequency plots and the results of the significance test.

Due to bad data, one subject could not be included into the analysis. The data of 10 subjects (7 male and 3 female) was remaining.

## 3.1 Power spectral density

The power spectral density (Figure 15) shows a very high peak within the alpha range at 11.5 Hz for C3 and C4 in the resting condition and a lower peak for conditions including movement. A second peak can be seen in the beta region around 23 Hz.

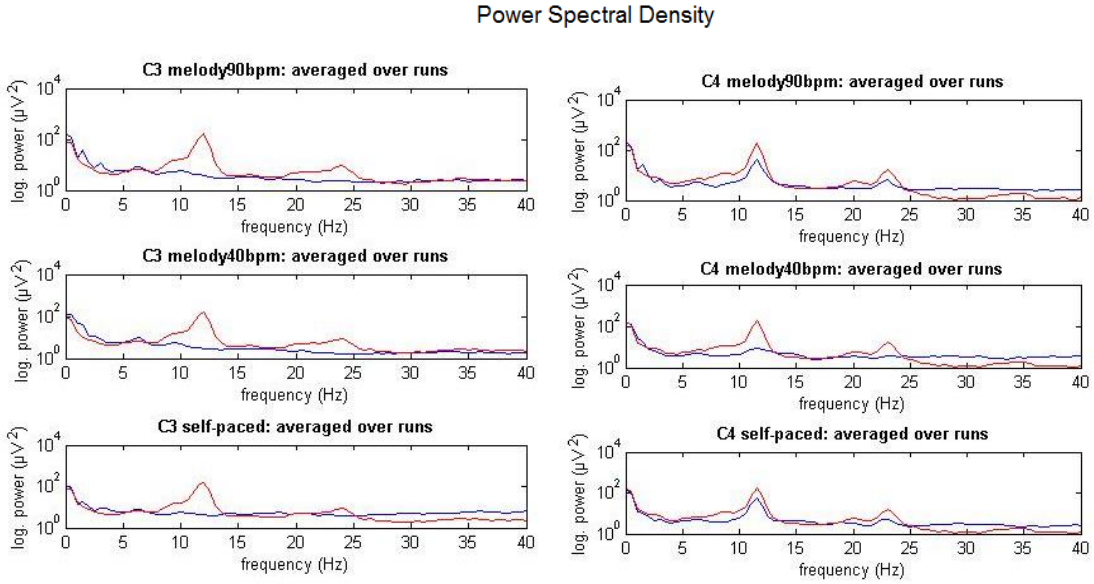


**Figure 15:** Spectral density for C3 and C4 from subject DL1, showing activity at rest (red) and movement (blue). The displayed frequencies are from 0 Hz to 40 Hz and the power is in logarithmic scale.

## 3.2 Topographic visualization amplitude modulations

Figure 16, 17 and 18 show the topographical map of the alpha desynchronization in dB for each subject.

### 3.2.1 Fast audio files – 90bpm

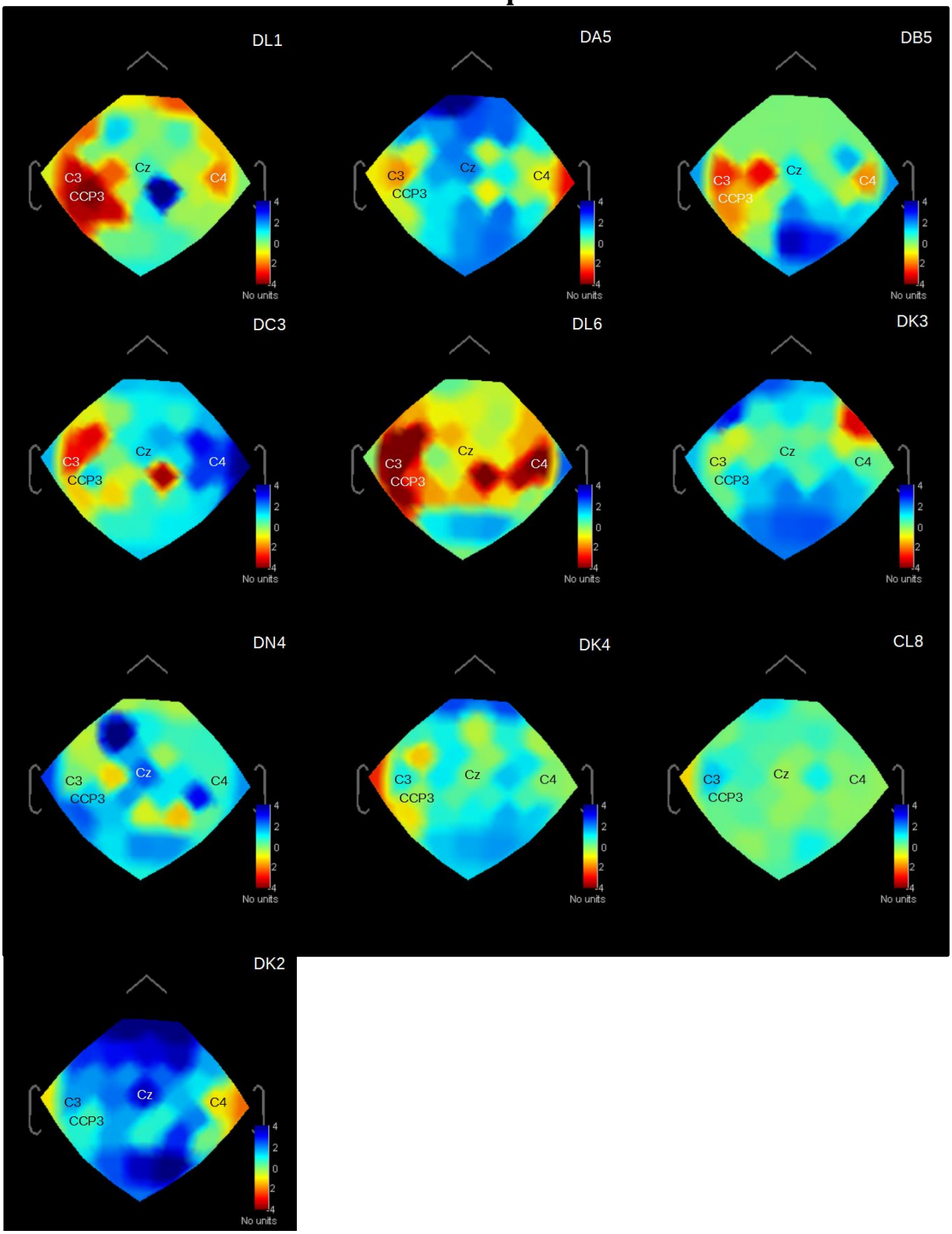


**Figure 16:** Topographical map of the amplitude modulations in dB for fast audio files for each subject.

### 3.2.2 Slow audio files - 40bpm

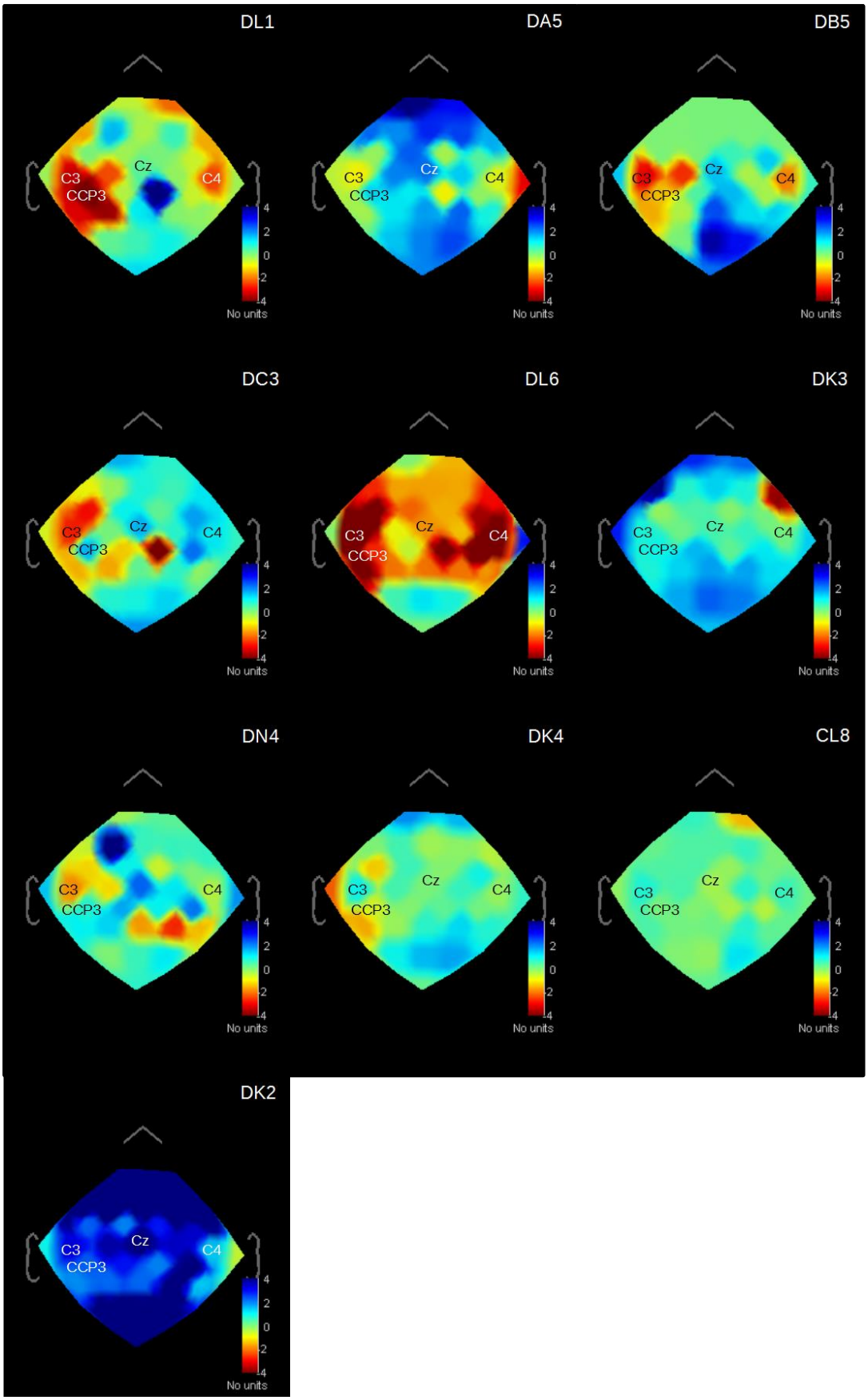


**Figure 17:** Topographical map of the amplitude modulations in dB for slow audio files for each subject.

### 3.2.3 Self-paced

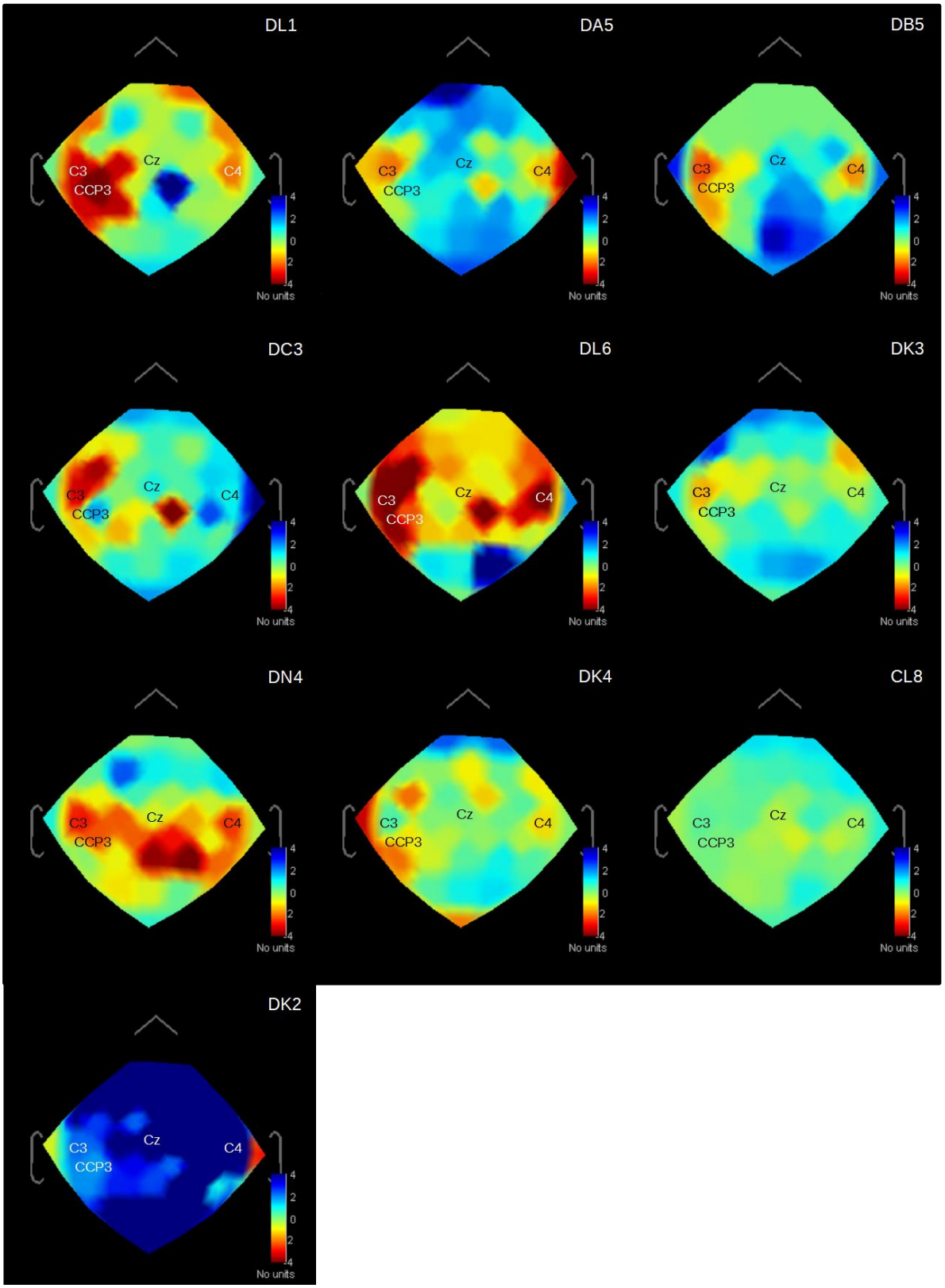


**Figure 18:** Topographical map of the amplitude modulations in dB for self-paced recordings for each subject.

Figure 19 shows the topographic map of the three conditions for three example subjects. It can be seen that the plots look very similar to each other.

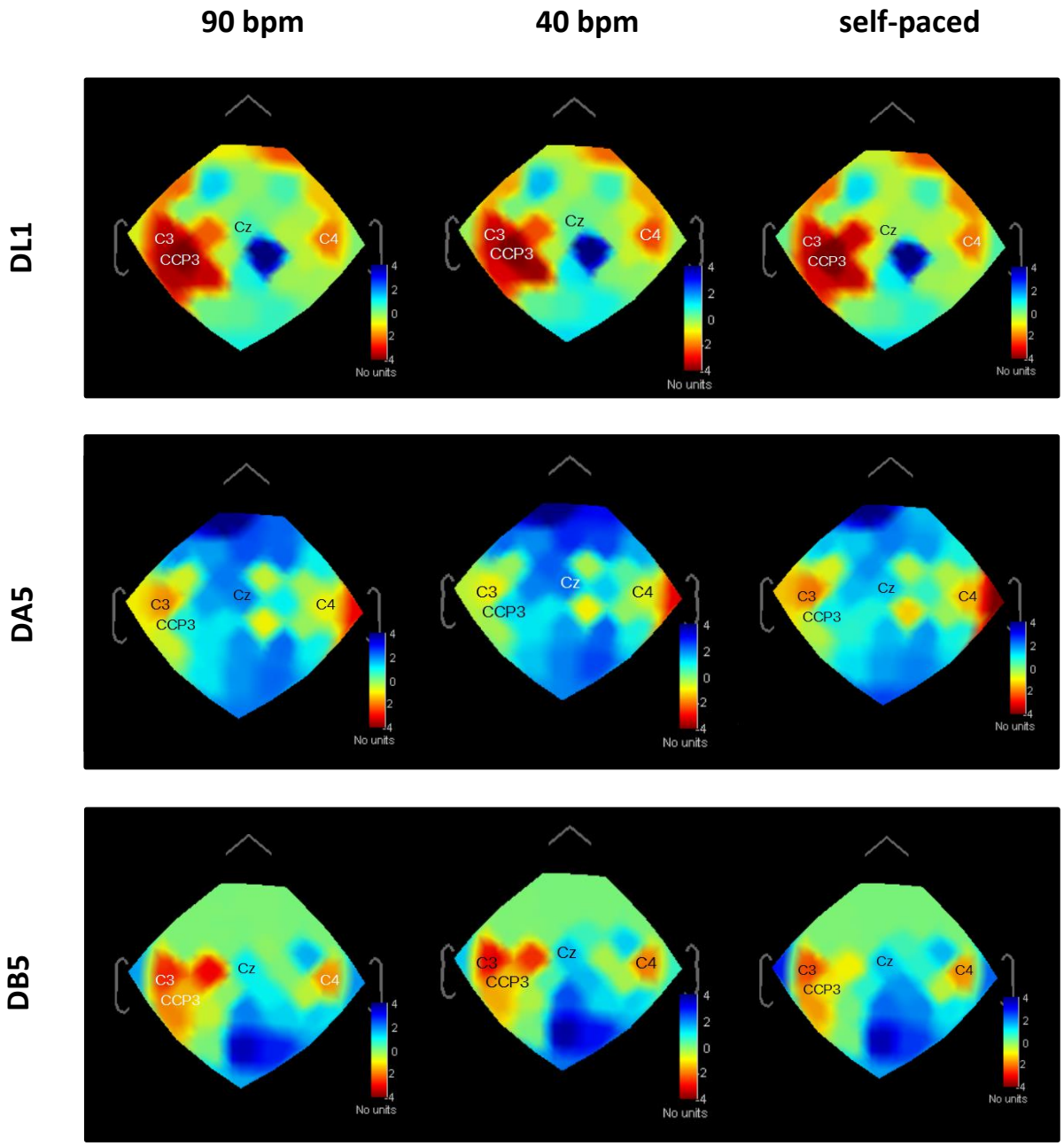


**Figure 19**: Topographic maps for subjects DL1, DA5, DB5, showing all three conditions compared to each other.

## 3.3 Time-frequency plots of movement phase-related activity modulations

The following time-frequency plots display the dynamic amplitude modulation during the movement for fast and slow melody for subject examples (Figure 20 – Figure 23) and for the group analysis (Figure 24). The synchrony of related networks can rhythmically be seen related to the movement sequence in beta modulations. Red colour represents ERD and blue ERS. A colour coded change (varies von -1 to +1) with a value of 0.1 shows a 10% change in the amplitude. The time zero represents the actual tap.

Figure 20 shows the movement pattern in the beta band. The minimum of the ERD is at time zero for C3 (Figure 20a) and slightly after zero for C4 (Figure 20c). The pattern in Cz is slightly shifted for fast melody (Figure 20b).

The slow melody displays inhomogeneous patterns (Figure 20d, e, f).

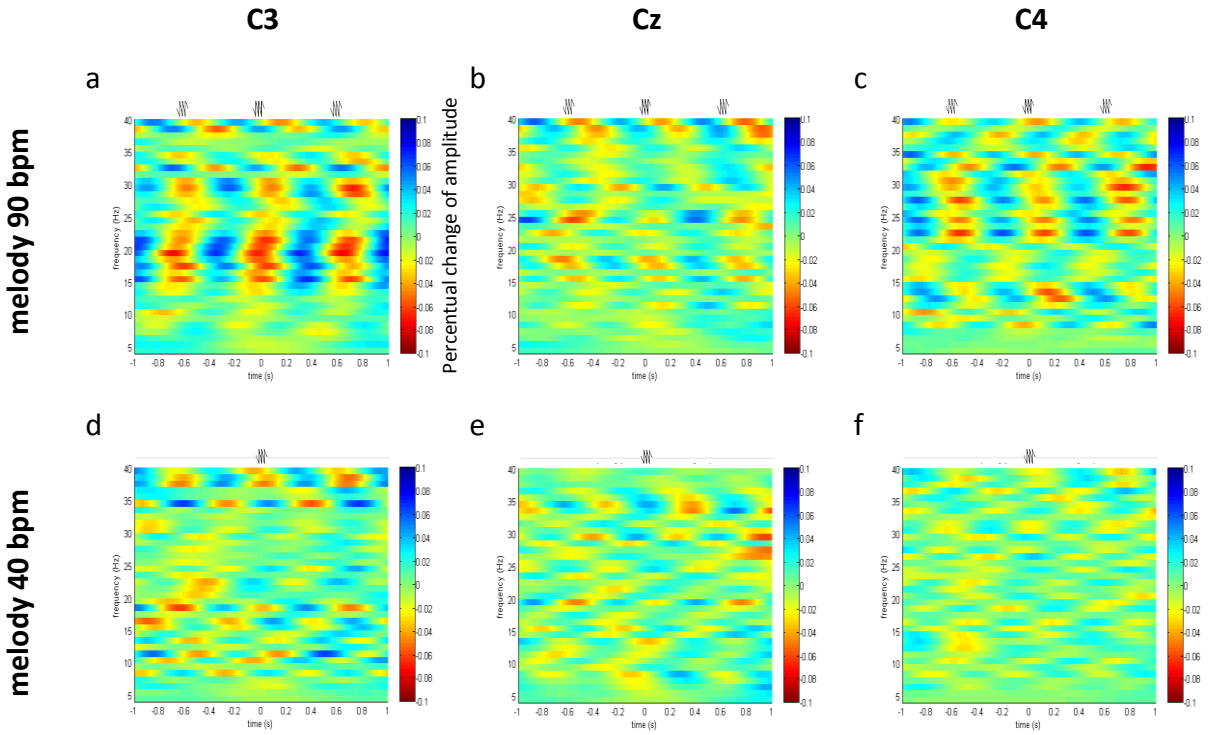


**Figure 20:** Time-frequency plots for subject DN4 for both slow and fast audio files for electrodes C3 (a, d), Cz (b, e) and C4 (c, f). At the very top of each plot the auditory stimuli can be seen, for fast melody the stimuli occurred every 0.66 s and for slow melody the time between the stimuli was 1.5 s.

Figure 21a, b, c show a pattern in the alpha band for fast melody that is different to the one in the beta band. This can also be seen in the plots for slow melody but in the beta band for Cz (Figure 21e) and the high beta band for C4 (Figure 21f) a pattern is obtainable that does not fit with the audio stimulus, it looks similar to the movement pattern in the beta band for fast movement. Therefore the plots show different patterns in alpha and in beta bands, respectively, but no significant difference between fast and slow movement in the alpha band.

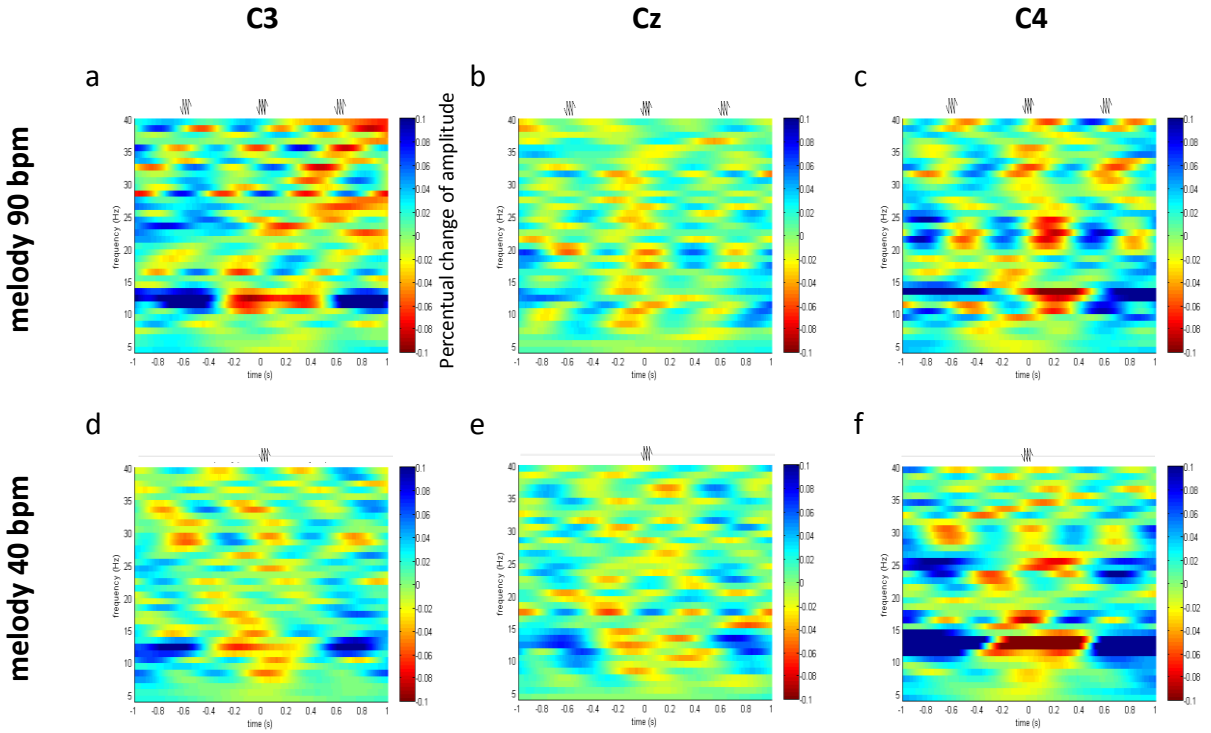


**Figure 21:** Time-frequency plots for subject DL6 for both slow and fast audio files for electrodes C3 (a, d), Cz (b, e) and C4 (c, f). At the very top of each plot the auditory stimuli can be seen, for fast melody the stimuli occurred every 0.66 s and for slow melody the time between the stimuli was 1.5 s.

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In Figure 22, the pattern of movement that can be seen has the same frequency for slow and for fast movement.

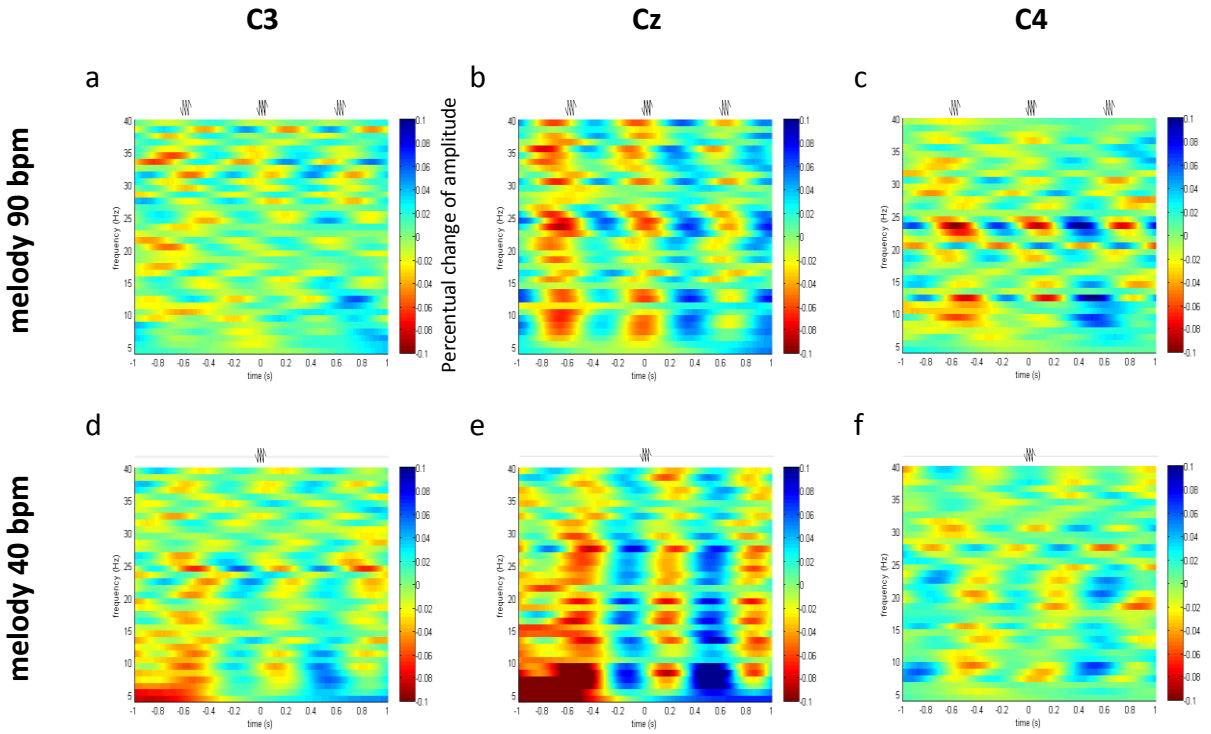


**Figure 22:** Time-frequency plots for subject DL1 for both slow and fast audio files for electrodes C3 (a, d), Cz (b, e) and C4 (c, f). At the very top of each plot the auditory stimuli can be seen, for fast melody the stimuli occurred every 0.66 s and for slow melody the time between the stimuli was 1.5 s.

.

C3 in Figure 23a for fast melody shows a very intense and steady activation from 5 up to 40 Hz, which is an indication for an artefact. In Cz (Figure 23b) and C4 (Figure 23c) for fast movement the typical movement pattern can be seen in the beta band.

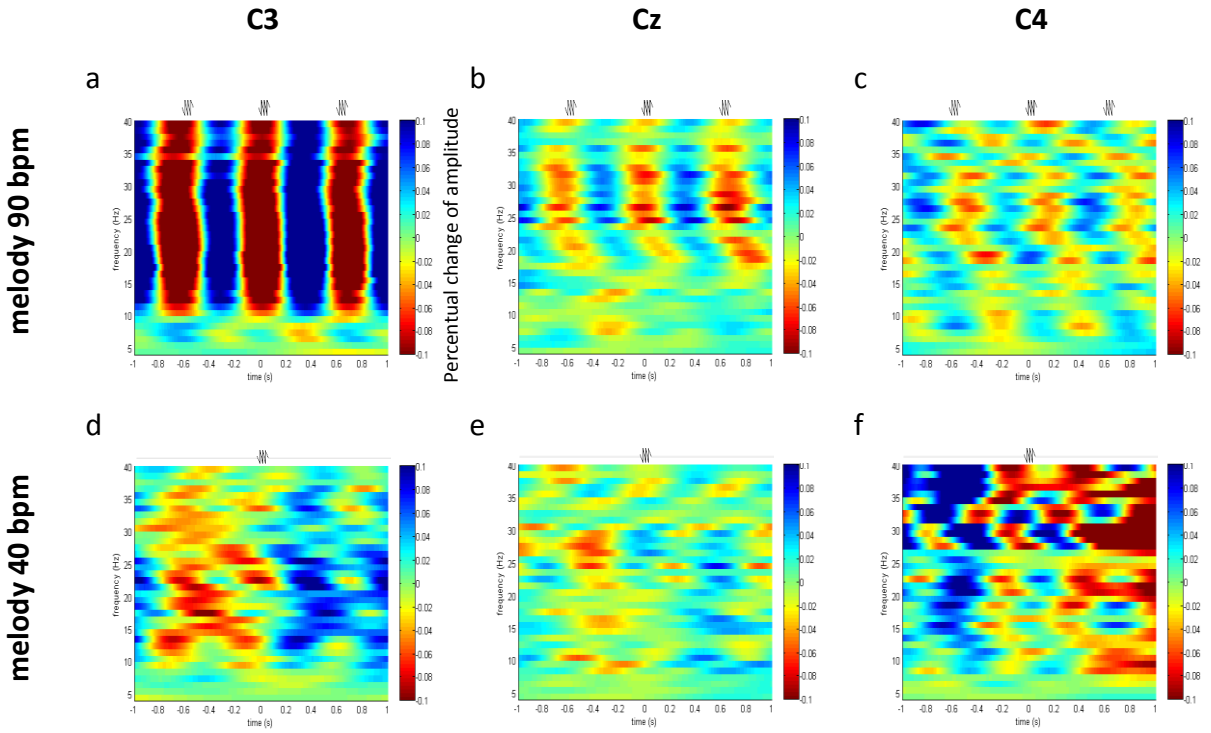


**Figure 23:** Time-frequency plots for subject CL8 for both slow and fast audio files for electrodes C3 (a, d), Cz (b, e) and C4 (c, f). At the very top of each plot the auditory stimuli can be seen, for fast melody the stimuli occurred every 0.66 s and for slow melody the time between the stimuli was 1.5 s.

.

Time-frequency plots were averaged over all subjects to get a group analysis (Figure 24).

The typical movement pattern can be seen in C4 for the fast melody (Figure 24c). The minimum of the ERD is not at the time zero but slightly afterwards. The plot for C3 (Figure 24a) shows a very intense activation from 10 up to 35 Hz. Averaging the results for the slow melody shows very inhomogeneous plots (Figure 24d, e, f).

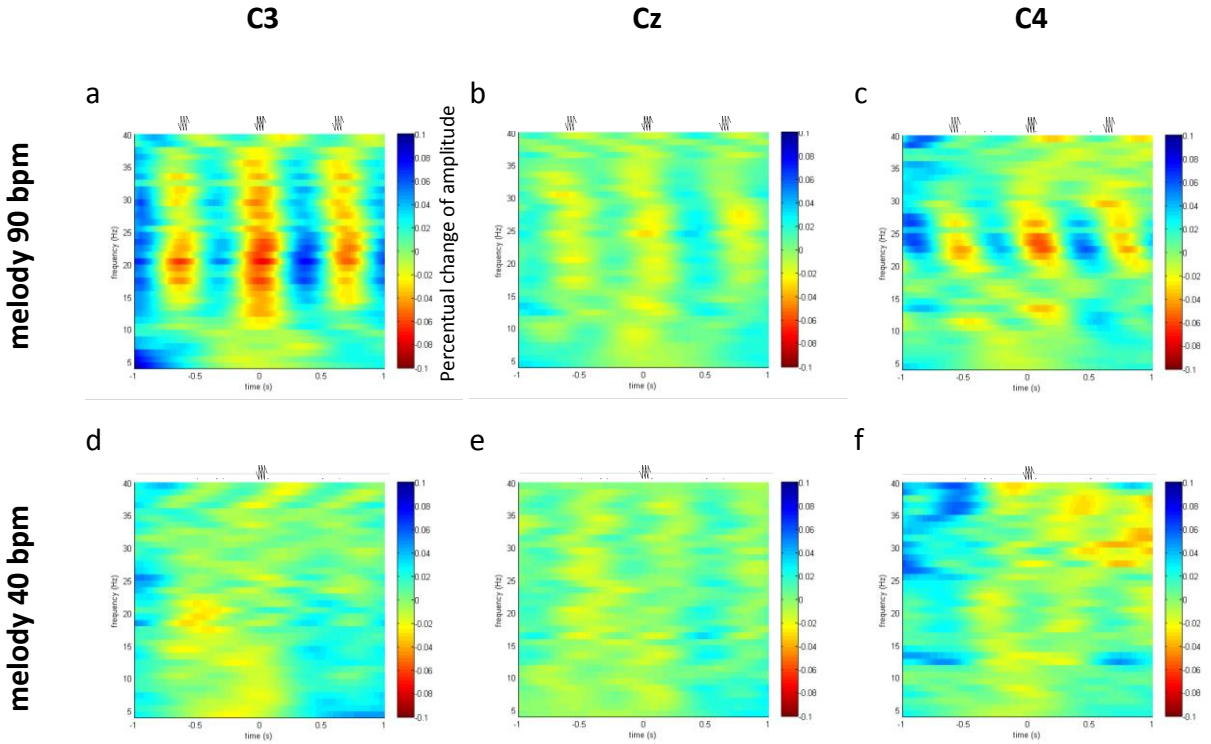


**Figure 24: Time**-frequency plots averaged over all subjects for both slow and fast audio files for electrodes C3 (a, d), Cz (b, e) and C4 (c, f). At the very top of each plot the auditory stimuli can be seen, for fast melody the stimuli occurred every 0.66 s and for slow melody the time between the stimuli was 1.5 s.

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## 3.4 Significance test

The amplitudes of the alpha peaks were determined manually for each subject using the power spectral density data. At exactly this frequency the amplitude modulations of the relation between activity to rest were calculated in dB and compared to each other.

As a first check the significance of the difference of the three conditions a boxplot with the values of the alpha peaks was plotted (Figure 25). It can be seen that the boxes do not differ a lot comparing the three conditions for the electrodes CCP3, C3 and C4.

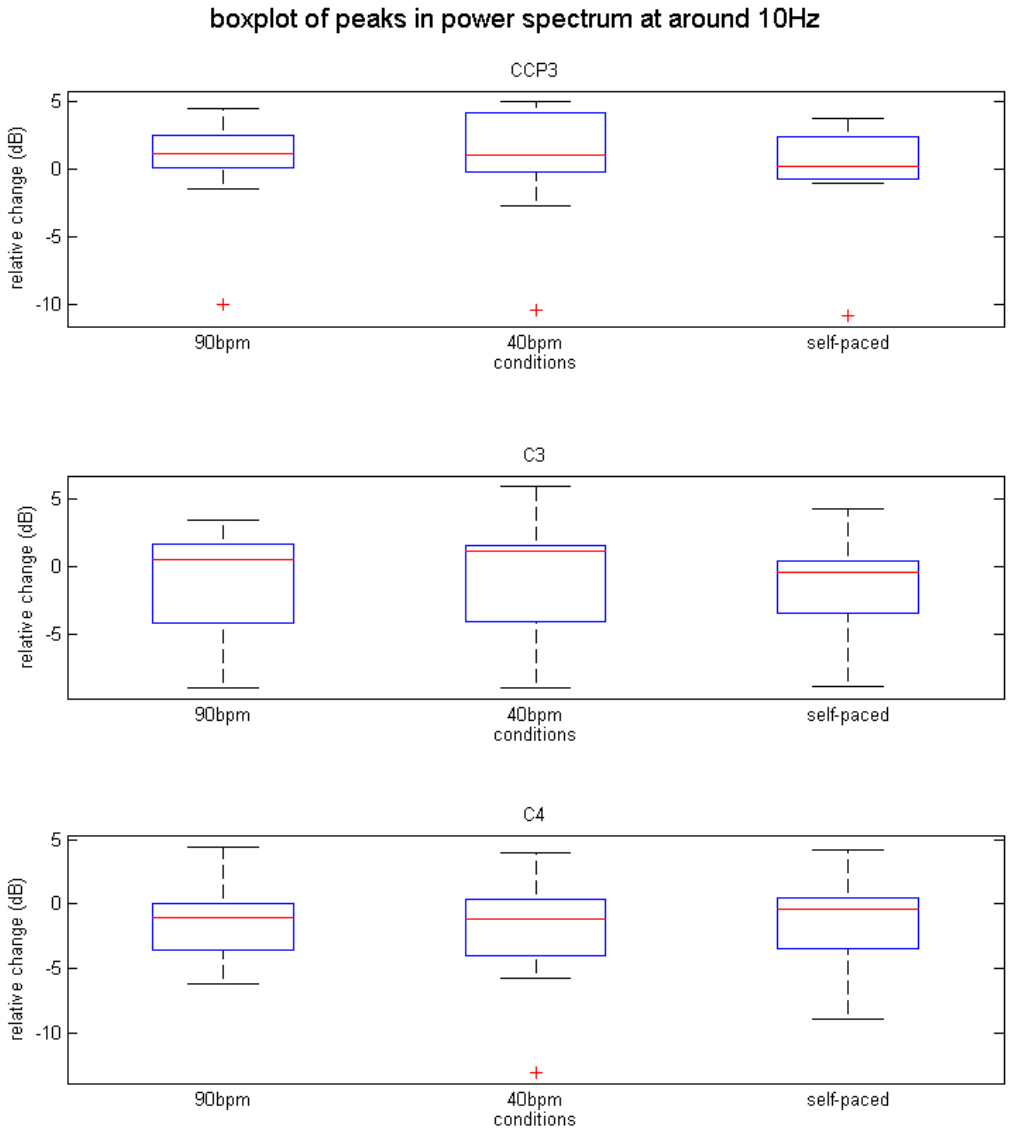


**Figure 25:** Boxplot showing the distribution of the values of the peaks in the μ-rhythm in CCP3, C3 and C4.

Table 3 shows the p-values of the performed Friedman's test for C3, C4 and CCP3 comparing the three conditions – fast melody, slow melody and self-paced – against each other.

With p-values higher than p=0.05 no significant differences were observed.

**Table 2:** p-Values for C3, C4 and CCP3 calculated by Friedman's test, comparing all three conditions against each other.

| | **p-Values** |
|---|---|
| **C3** | 0,4066 |
| **C4** | 0,6703 |
| **CCP3** | 0,7408 |

# 4 Discussion

In this thesis the influence of music on brain activity while finger tapping was investigated. The EEG was measured while tapping to slow (0.66 Hz), fast (1.5 Hz) audio tracks and during self-paced finger tapping without any music.

The power spectral density looks specific for voluntary movement tasks. Generally a narrow-band peak indicates the synchrony in underlying neuronal populations induced by neuronal oscillations of frequency-specific networks [7], [8], [38], [48]. Frequency-specific amplitude modulations were suggested to represent frequency-specific large-scale networks [7], [9], [46].

The μ-rhythm is frequency and amplitude-wise similar to the alpha rhythm but observable over the motor cortex. It is detectable when the body is at rest. It is not equally visible in every mature subject. Performing, visualizing or just imagining motor actions supress the μ oscillations and is interpreted as so-called desynchronization of the neuronal populations being in synchrony [30], [37], [38]. To measure this effect electrodes covering C3 and C4 areas are used which are located over the precentral gyrus [22], [31].

This phenomenon explains why the obvious peak in the frequency spectrum (Figure 15) at 11.5 Hz is very high for rest compared to activity.

An 1/f-decay can be seen throughout the whole spectrum, which is not as strongly expressed as typical, although a logarithmic scale was applied. The reason for this decay is the fact that the amplitude and frequency behave inversely proportional to one another [31]. This also explains the smaller peak in the beta band at 23 Hz.
This arch-shaped double peak in alpha and beta bands is typical for voluntary movement and can be detected in the sensorimotor areas at around 10 Hz and 20 Hz which is exactly what can be seen in Figure 15 [38]**.**

The topographic plots show the change of state in dB comparing movement to rest. For these sustained amplitude modulations the decrease in the alpha band from 8.5-12 Hz was

averaged to show the desynchronization pattern. The desynchronization is displayed in red and can be seen in all three conditions – fast audio track, slow audio track and self-paced tapping – over the motor cortex. The left hemisphere shows higher activations, therefore a higher desynchonization can be seen, because the left motor cortex area around C3 represents the corresponding contralateral area for the right hand. A clear activation can be seen in 7 out of 10 subjects at C3 and CCP3. The patterns corresponding to DL1 and DL6 show this behaviour very clearly.

The activation patterns for all three conditions look very much alike. Nevertheless, the significance test conducted with the values of the alpha peaks shows no significance, (Table 3) all calculated p-values are far above 0.05.

Based on these findings, the hypothesised assumption that tapping to music compared to rest might show bigger areas or higher activation has to be rejected.

The reason for seeing activation also in the right hemisphere is that on the one hand as a response to nearly all tasks a topographically widespread lower alpha desynchronization is obtained [38]. On the other hand it might also be an active suppression of the left hand movement [38]. Moving is a basic need of humans, therefore an active suppression occurs when being at rest. This phenomenon is described as ERS which explains the observable brain activity being at rest. Furthermore, this might explain the lack of significant differences between movement to music and self-paced movement. Even pure imagination of a hand movement will show similar activation patterns in the brain compared to the real movement [39].

Figure 26 is additionally explaining the difference between sustained and dynamic amplitude envelopes. For showing the alpha desynchronization in the topographic visualization the lower part of the plot was used, plotted in green and blue. In contrast to the beta-modulations for the time-frequency plots, a lower baseline to show the modulations within the movement was used (upper part in the plot, displayed in red and magenta) [47].

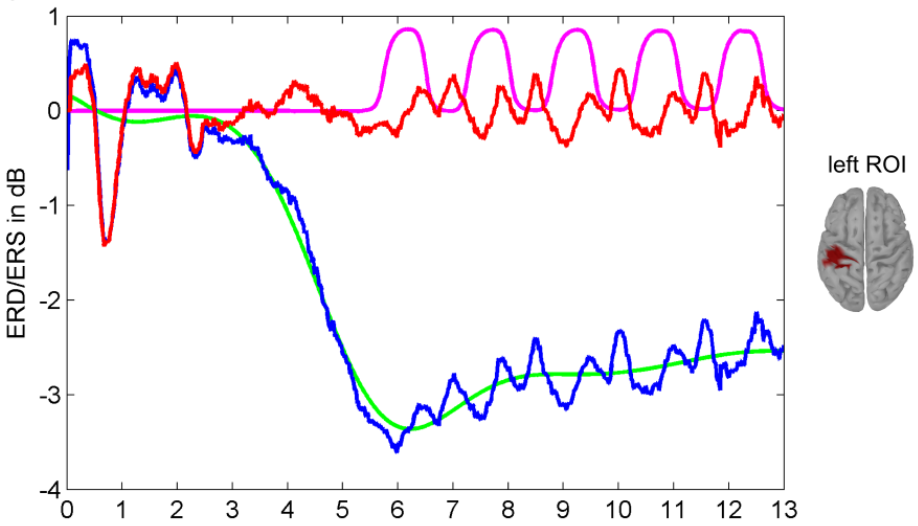


**Figure 26:** Distinguishing sustained and dynamic amplitude envelopes, showing the original, sustained amplitude envelope (blue), the low pass filtered signal (green), the high pass filtered amplitude envelope (red) and the actual finger movement (magenta) in a study where subjects had to move their finger in the rhythm that was indicated beforehand by blinking of a dot appearing on the screen. This plot shows the patterns for the left ROI, which is based on the centres of the typical beta ERD patterns. (modified from [47])

In the time-frequency plots the beta modulations can be seen. As described above the units describe the percentage of relative change in activity, although changes of ±10% are rather small effects.

Due to the appearance of today unexplainable effects in some plots, a comprehensive interpretation of the result is rendered impossible. However, in most cases the pattern of movement is recognizable.

An expected desynchronization can be seen at time zero, which represents the actual tapping time for the example in Figure 20. The minimum of the ERD is for C3 to be found at time zero, while it is shifted in C4 for about 1/10 of the time. This might be due to the fact that those areas are networking and the information reaches C4 slightly later than C3. The observation that the beta modulation pattern is more aligned with alpha modulations in contralateral (C3), compared to ipsilateral areas (C4) is in line with previous studies [47].

C3 in Figure 23a for fast melody is most likely interfered by artefacts, since a very intense and steady activation can be seen from 5 up to 40 Hz. This is a typical indication for electromyography, therefore unwanted muscle activity, or cable swing.

Contraindications for other subjects are that if there were systematic errors causing artefacts the artefacts would be seen throughout all electrodes and conditions for one subject. Also the fact that the minimum power of the ERD lies at the cue argues against the presence of artefacts. Those would cause the appearance of a maximum at this time. Further, narrow-banded beta patterns in some of the subjects (Figure 22c and Figure 22d) were spatially well spotted. These findings moreover suggest that these patterns are caused by electrocortical activities of the brain.

Interestingly, the pattern of movement that can be seen seems to have the same frequency for slow and for fast movement in some subjects like observed in Figure 22. Notably Figure 21e and Figure 21f show different patterns in alpha and in beta bands, respectively, but no significant difference between fast and slow movement in the alpha band.

Also the group figure (Figure 24) shows recognisable movement patterns in the plots for fast movement. Due to the inhomogeneous patterns for the slow movement experiments any further interpretation is hard to make. The pattern that can be seen from low to high frequencies in the plot for C3 for fast melody (Figure 24a) is because of the very intense overlaid artefact of subject CL8 (Figure 23a).

The observed two different activation patterns for dynamic and sustained modulations might be explained by the activation of two different networks. The networks for sustained modulations might be responsible for stopping the suppression during movement and play a role in upregulating excitability in the corresponding areas corresponding to the body parts which are moved [27], [29], [38]. On the other hand the networks for dynamic modulations change their synchrony according to the movement of the finger. These might have specific functions like sensorimotor prediction and integration signified by those dynamic amplitude modulations [47].

## 4.1 Conclusion

Taken together, no significant influence of music on brain activity while finger tapping could be observed. For further studies a possible way of minimizing artefacts and outliers is to increase the number of subjects. Although the hypothesis had to be rejected, this research revealed some interesting findings that can be utilized for further investigations. As mentioned above using music as a part of rehabilitation can lead to improved performance and progress results in patients. A deeper understanding of the underlying mechanisms might enable health care professionals to establish even more efficient therapeutical approaches.

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