Neurotactile Integration

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***Abstract*—The field of neural representation of sensory integration is an advanced topic with complex processes. The mechanisms of the brain are far from fully understood and are in need of further development to be implemented in clinical usages such as neuroprosthetics. The purpose behind this project is to further the knowledge of neurotactile integration as well as processes and mechanisms of the brain by studying event related potentials (ERPs) elicited by an applied non-invasive electrotactile stimuli. This was done in collaboration with the department of Biomedical Engineering by students at the Faculty of Engineering, Lund University. Access to the university's facilities were granted, including the EEG-lab where testing was conducted. The methods used in this project are mainly laboratory experiments and MATLAB analysis of collected data. Two experiments have been performed, both with the same setup and purpose to test whether the credibility of the stated thesis. They were performed with Labview-based scripts to drive a read stimulator with an electrode generating electrical pulses. Data was recorded with a 64-channel electroencephalogram (EEG) cap connected to the Quattrocento amplifier to study electrical stimuli registered by the brain. The analysis was made with an EEG-processing code obtained by the supervisor, a signal processing code to extract better quality data of measured EEG-recordings and extract ERPs using pulse generated triggers. The most important results of this project was to be given by the ERPs representations of sensory feedback perception. These did unfortunately not yield significant results and further work needs to be done for the progress of this project.**

I. Introduction

THE field of bionic limbs with an interface to the nervous system and the ability to respond to neural stimuli and give sensory feedback has seen significant growth in recent years. The prosthetics perform well in clinical trials as well as in home-use trials even though they have limitations. The study of motor control is important in the development of these prosthetics and even though this is well studied in able-bodied individuals it is far less extensive for amputees. The neural interfaces are a big challenge in the field with the demand for high quality readings of neural activity while still wanting to limit the degree of invasiveness. When given high quality readings the next challenge is to decode the collected information by implementing suitable algorithms. [1]

Event related potentials or ERPs are good representations of brain activity, potentials as a response to either external stimuli or from within the brain itself. The ERP is often described by its components which are named after their characteristics in terms of polarity and latency. An example of this is P300 describing a positive peak with an latency of 300ms. [2]

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The evoked potentials of the brain vary depending on the nature of the applied stimuli, which has been widely observed and documented. Studies has investigated somatosensory evoked potentials (SEPs) in response to sensory generated external stimuli, showing distinct differences between the SEPs given from tendon vibration and those from cutaneous stimulation. This also showed that the SEPs were dependent on frequency as well as the amplitude of the tendon vibration. [3]

Another study investigated the P40, N60 and P100 components of SEPs and observed that they were related to different stages of sensory processing. The P40 related to initial processing of sensory information while N60 was related to detection of change in sensory input, P100 was related to conscious perception of the sensory stimulus. Overall the study broadened the knowledge of the brain's function and mechanisms. [4]

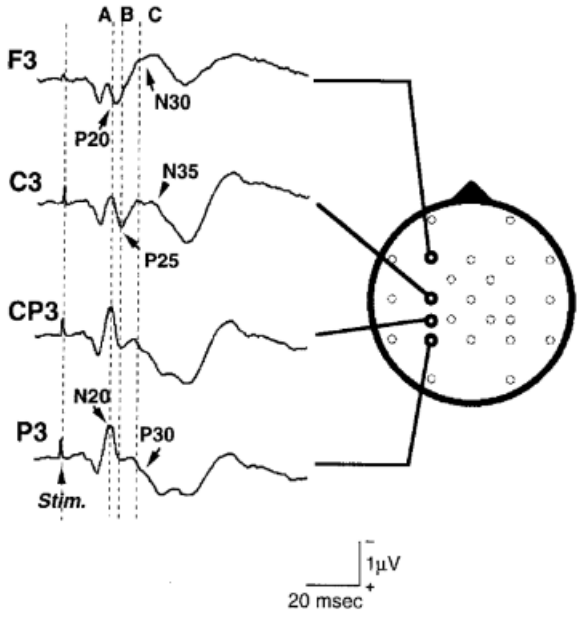

Fig. 1. Sensory evoked potentials for different channels [3]

Even though the sensory and motor cortex are visualised as different regions their functions are closely related. Motor activity produces a large amount of sensory input and the sensory cortex integrates these inputs with its own. Additionally the motor cortex affect the sensory by creating expectations, as certain movement is expected to create sensory input the response of the sensory cortex to this is shown to be lower than that from unexpected input. [5]

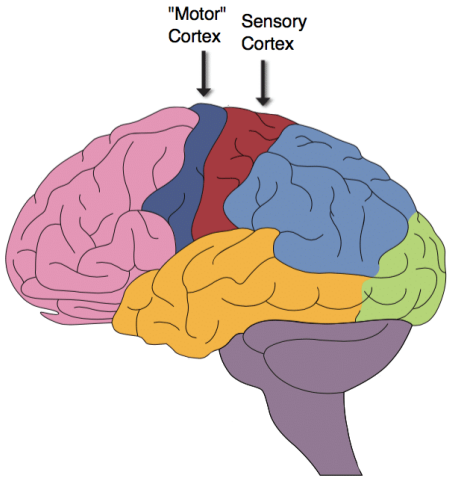

Fig. 2. Sensory and motor cortex in brain. [6]

Earlier studies have mainly been done on stimuli in isolation but recently interplay between different senses has been of increasing interest. The integration of several different stimuli at a time is instead of integration referred to as interplay as one stimuli may affect the integration of another on such a level that it is perceived fundamentally different. [7] The McGurk effect is an example of this where visual stimuli interferes with auditory resulting in hearing a sound different to the one actually uttered. [8]

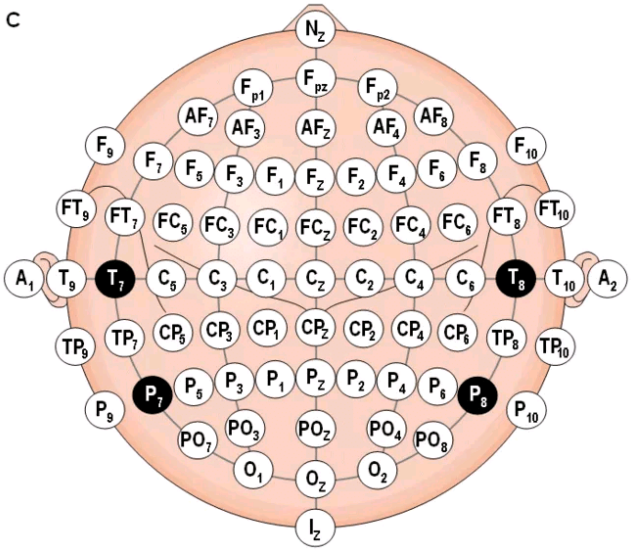

Fig. 3. The distribution map of 64-channel EEG electrodes in human brain. The channels are labeled as shown in the figure with measurement sites corresponding to their physical position on the scalp. [9]

Earlier studies have laid the ground work in the field showing specific neural responses to stimuli. By studying these processes closely we can unveil the underlying mechanisms of the brain and learn how the responses vary given different stimuli. By studying the cognitive functions of the brain, current knowledge can be extended and new understanding might be acquired for implementations in many fields such as treatment of disorders or development of neuroprosthetics.

With the knowledge of earlier work we can hypothesize to see activations in the sensory cortex of the brain in the opposite side of the body to a limb receiving electrical stimulation. These SEPs, averaged from multiple trials, will be characterised as a sudden increase in neural activity shown as large peaks in contrast to the relatively flat nature before stimulation. This is seen in Fig. 1, before stimulation the graphs are quite flat in contrast to post stimulation where activity is of far greater amplitude.

OT Biolab is a software used in EEG-recordings to collect and store the data measured by the BIO Elettronica equipment. These include the EEG-cap and an amplifier, more specifically the Quattrocento amplifier. OT Biolab is compatible with the software Labview that is used to generate electric impulses in sensory experiments, enabling the collection and storage of this data together with that of the EEG. In our project this will be used together with the the software Matlab and specific Matlab toolboxes. These are Signal Processing Toolbox as well as Statistics and Machine Learning Toolbox which are used to implement specific functions for our processing.

This report will present the steps taken to study the neural responses to different stimuli and the processes implemented to analyze the recorded electroencephalogram (EEG) data. Two experiments will be described in detail. In the first experiment electroencephalography is implemented to record the neural response to applied stimuli and in the second it is repeated in a shielded room. The processing of the collected data will be thoroughly presented, describing the methods used as well as demonstrating the extracted results. These results will be discussed in relation to the thesis and a conclusion will be made.

II. Method

A. Experiment 1: Brain responses to electrical stimuli

Participant: Kalle Svensson
Head scientist: Julius Cewers
Date of experiment: 2023-02-23
Material used:

- Quattrocento amplifier, BIO Elettronica
- OT Biolab, BIO Elettronica
- EEG-cap, BIO Elettronica
- NI USB-6218, National Instruments
- Labview, National Instruments
- Circuit board for generating electric impulses
- Reference electrode
- Electrode for delivering impulses
- Spectra 360 Electrode Gel, Parker Laboratories INC

The experiment was performed by Julius and Kalle without supervision after getting acquainted with the setup and

software.

The electrode generating the electrical stimulation pulse is connected to the tibialis anterior muscle on the right leg, and a reference electrode is connected slightly above the foot on the front of the right leg. The 64 channel EEG-cap was put on Kalle's head, covering the whole brain and adjusted for a tight fit. The cap was connected to the amplifier which in its turn was connected to the computer with the essential software. Conductive gel was administered between the electrodes of the headset and Kalle's head by syringe.

The impulses were generated with the help of the computer program Labview and a circuit board, to which the electrodes were connected. A plastic box was put on top of the circuit board because of a blinking light, to remove potential disturbance threat for the participant. The EEG-datasets were recorded and collected by the software OT Biolab, which is compatible with the BIO Elettronica equipment.

During the performance procedure, the surroundings were quiet to remove any type disturbance for the experiment. The participant Kalle had to sit still and keep his mind clear, to limit the interference of other brain functions. During the experiment three sets of recordings were done with the following parameters:

Set 1:

- Duration of pulse: 0.1 s
- Frequency: 10-20 Hz
- Current: 4-6 mA
- Number of repetitions: 100
- Duration of recording: 27 minutes
- Stimuli intervals: 3-5 s

Set 2:

- Duration of pulse: 0.3 s
- Frequency: 3-20 Hz
- Current: 4-6 mA
- Number of repetitions: 100
- Duration of recording: 26.5 minutes
- Stimuli intervals: 3-5 s

Set 3:

- Duration of pulse: 0.5 s
- Frequency: 2-20 Hz
- Current: 4-6 mA
- Number of repetitions: 100
- Duration of recording: 26.5 minutes
- Stimuli intervals: 3-5 s

The varying duration of pulse and frequency were set up to investigate the significance of parameters. The pulse currents set up for the experiments are above the participant's sensory threshold (obtained by previous testing) to ensure the perception of the electrical stimuli. The number of repetitions is necessary for ERP analysis. The stimuli intervals were chosen to make sure the brain response was neutralized before exposure to new stimuli.

B. Experiment 2: Improved with shielded room

Head scientist: Jia Liu
Date of experiment: 2023-03-30
Material used is the same as in Experiment 1:

- Quattrocento amplifier, BIO Elettronica
- OT Biolab, BIO Elettronica
- EEG-cap, BIO Elettronica
- NI USB-6218, National Instruments
- Labview, National Instruments
- Circuit board for generating electric impulses
- Reference electrode
- Electrode for applying impulses
- Spectra 360 Electrode Gel, Parker Laboratories INC

The experiment was performed by supervisor Jia Liu and co-workers. The setup was similar to Experiment 1, by using a electrode generating the electrical pulse connected to the anterior tibialis muscle and a reference electrode to above the right foot. The 64 channel EEG-cap was put on the participant's head supported by a conductive gel between the scalp and the electrodes.

During the performance procedure, the surroundings were improved compared to the previous experiment with a shielded room. By implementing a shielded room, potential threats from the surrounding environment is decreased.

During the experiment two sets of recordings were done. The first recording had the electrode-setting in the EEG-cap put in monopolar-differential mode, same as Experiment 1. The second recording had the setting differential-differential. Data-sets were recorded and collected by the supervisor Jia Liu and then forwarded to further analysis.

C. Data analysis

The softwares used in the analysis of data are MATLAB and OT Biolab. All datasets from the experiments were collected and given as files in OT Biolab. To analyze the data it was necessary to convert into MATLAB-files. The analysis of data was done in MATLAB and the code for processing the EEG-data was given by the supervisor. The code contains signal processing algorithms to extract good quality data from the raw 64 channels EEG-data and extract ERPs using pulses triggers.

The processing of the data collected from Experiment 1 was visualized in MATLAB to check for potential bad channels (channels that give data with too high amplitude, too low amplitude or overly irregular data). Bad channels were removed and replaced using surrounding channels to improve the quality of the data. This was done by replacing the data of these channels with the average data of two nearby channels of better quality and thus removing the effect that this abnormal data would have had on the finished product. The sampling frequency was set to 512 Hz. Then the processing code applied a series of notch (47-50 Hz) and bandpass (1-30 Hz) filters to the data and were plotted against the raw data. The quality of the data was still bad

and no further analysis of this data was made.

The data from Experiment 2 was given by the supervisor and the same processing code was applied. First the data was visualized and bad channels, Fz and F2 (see Fig. 3), were removed and replaced with a mean of two nearby channels. The same series of notch and bandpass filters were applied. The filtered data was then plotted against the raw data and the quality of data was improved and able to further analyze.

Since only the motor and sensory cortex (see Fig. 2) is of interest, it is unnecessary to keep all the 64 channels (see Fig. 3). Therefore following channels were removed from the data: Fpz, F9, F3, FT9, FT10, T9, T10, TP9, TP10, P9 and P10. These channels were removed as they are all quite close to the ears and thus far away from the sensory cortex.

An Independent Component Analysis (ICA) was performed on the remaining 53 channels of interest to separate the brain activity from artifacts, such as eye movements and muscle activity. In the ICA twenty components were derived from the channels and these components represent almost all brain sources (more than 99 percent). By running the ICA a spatial representation of brain activity, a spectrogram, a PSD and the EEG-data as amplitude over time set were plotted.

Next step was trigger detection, it was done to identify the onset of the stimulus in the recorded data which is crucial in the analysis of ERPs. By identifying the onset of the stimulus the time of interest when studying the ERPs can be located.

For the segmentation of the data around the stimulus, the selected channels are C3, C4, C5, C6 and Cz which are the ones related to the sensory cortex. By running the segmentation code, two different representation plots were made of the ERP. A plot of variation of amplitude over time and a topography plot of brain activity.

III. Results

The unfiltered (blue) EEG-data from Experiment 1 is plotted against the notch and bandpass filtered data in Fig. 4. The data is of bad quality, seen by its greatly varying amplitude as well as the sudden and great reduction of activity between 5-7 (10^5) seconds on the x-axis.

In Fig. 5 the unfiltered (blue) data and the notch and bandpass filtered (red) data from Experiment 2 is plotted. The quality of this data is of significantly better quality than the data from Experiment 1. This is seen by the more continuous nature with less deviations than that of Fig. 4

After the ICA analyses, we extracted 20 ICA components, Fig. 6 shows one typical ICA component. The figure shows a topography plot (top-left) which is a spatial representation of brain activity. In the topographic plot activity is presented with varying coloring with the outer edges of the colorbar representing high activity. It also shows a spectrogram (top-middle) representing the time-varying frequency content of the

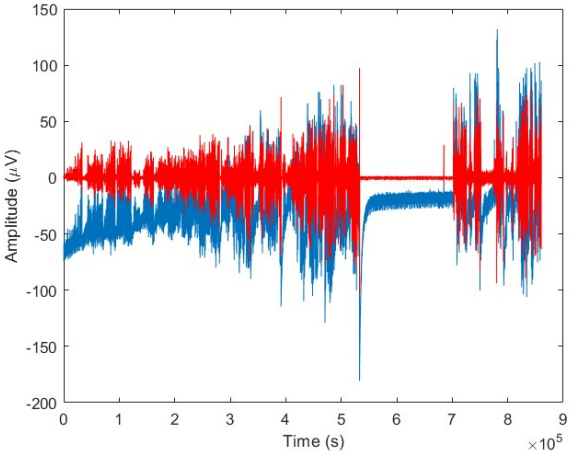

Fig. 4. EEG data from unshielded room. Filtered (red) and unfiltered (blue)

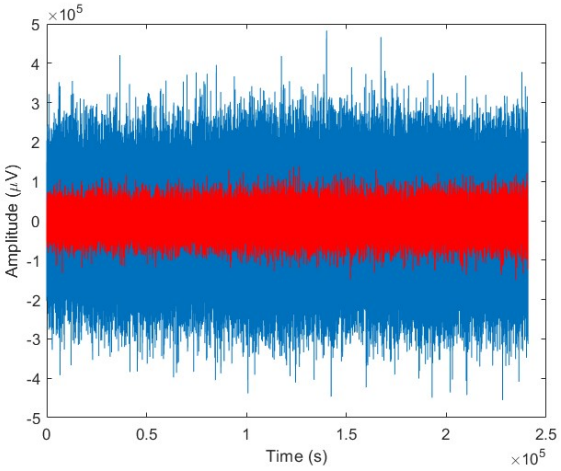

Fig. 5. EEG data from shielded room. Filtered (red) and unfiltered (blue)

recorded neural activity. The graph on the top-right is a power spectral density plot that show the frequency distrubition of the electrical activity of the brain. Finally at the bottom there is a figure of the EEG-data plotted as a time-series.

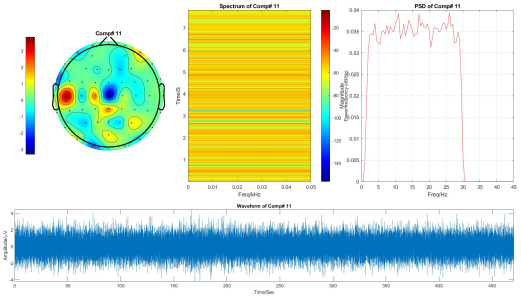

Fig. 6. Spatial representation of brain activity, spectrogram, power spectral density (PSD) and the EEG-data as its amplitude over time

Fig. 7 is showing the dataset before (top, red) and after

(bottom, black) running the ICA code. The plots look similar but differs with a factor of approximately 250 in amplitude.

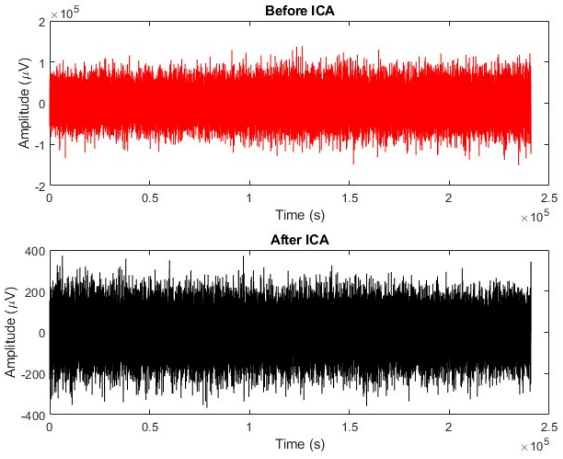

Fig. 7. Figures showing the EEG data before and after ICA.

The top plot of Fig. 8 is showing the electrical pulse amplitudes. The blue graph corresponds to the pulse given by the electrical stimulator. In the bottom plot, the same blue graph is plotted against the red graph as corresponds to the trigger detection.

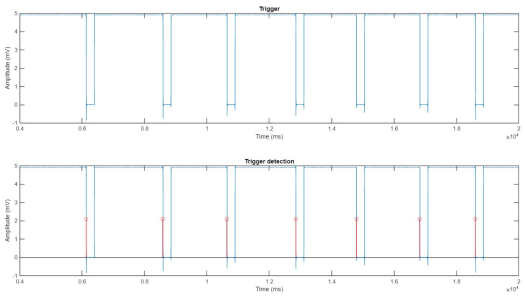

Fig. 8. Figures showing the triggers.

Fig. 9 represents the the mean evoked waveforms averaged from 100 repetitions in the time range of -50 to 200 ms stimulus onset from the selected channels C3, C4, C5, C6 and Cz. These channels are located for measurement of the sensory cortex and the time window displayed contains the time for a stimulation, thus the stimulus evoked waveforms should involve the sensory evoked potentials, the measurement was not successful though and significant SEPs were not found.

Fig. 10 shows three topographic plots representing the neural activity in the time windows of 40-55, 20-30 and 10-20 ms after stimulation. Here activation in the sensory cortex is expected and found but the data is still regarded as unsignificant as a consequence of the data in Fig. 11.

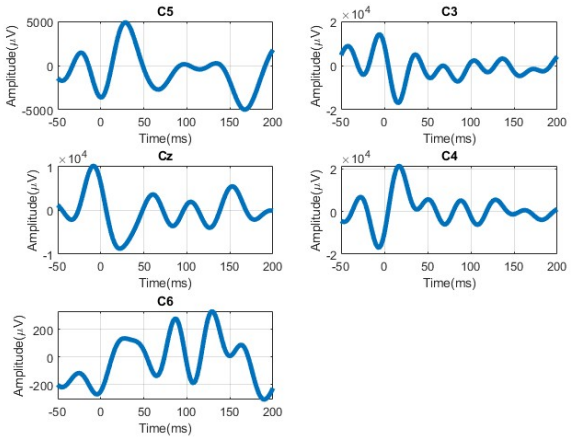

Fig. 9. ERPs of selected EEG-channels.

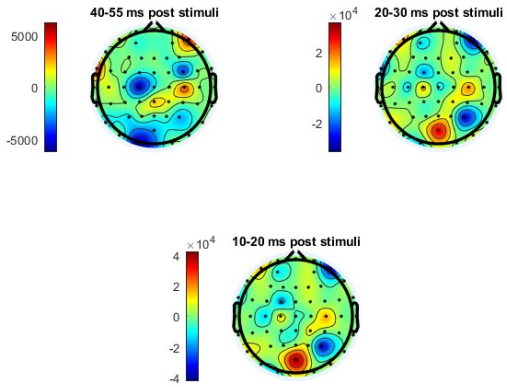

Fig. 10. ERPs at different time slots after stimulation.

Fig. 11 shows the topographic plot for the neural activity 30-20ms before stimulation. Here activation is unexpectedly seen in the sensory cortex.

IV. Discussion

The first experiment did not yield significant results. The reason behind this is most probably some sort of interference. This can be caused by electrical interference given the fact that the experiment was not conducted in a shielded room, inferior equipment limiting the resolution of the recording, insufficient protocol for testing the data or faults done when conducting the experiment. The initial hope was that the use of a shielded room was unnecessary but this experiment proved the contrary. Consequently the experiment had to be redone. Fig. 4 shows the data before (blue) filtration and after (red). Even though the filtration improves the reading it is still very low quality to such an extent that further processing is pointless. When compared to Fig. 5 it is seen that the amplitude is far smaller in Fig. 4 which could be caused by improper application of conductive gel between

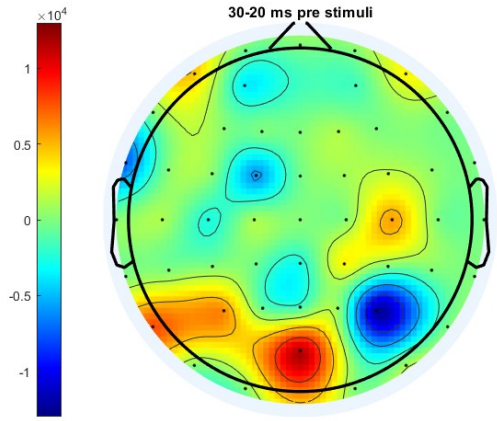

Fig. 11. ERPs at different time slots before stimulation.

electrodes and scalp thus limiting the strength of the signal. In experiment 2 modifications of the experiment were made to ensure higher quality readings enabling the collection of good results. This was done by performing the experiment in a new lab, with interference-shielding and better equipment as well as performed by our supervisor Jia Liu.

When the experiment was redone the retrieved data was significantly better but still not perfect. The newly retrieved data could without problem be processed but the expected SEPs could not be found. The purchase of new EEG-equipment is discussed to solve this problem. This shows the delicate nature of the field where highly sensitive equipment paired with a suitable (shielded) area as well as experienced personnel is essential. A successful experiment would have given us readings showing the brain's response to the applied stimuli as well as which parts of the brain activated. We would have seen different reactions to different stimuli that varied in the earlier mentioned parameters. Fig. 6 is an example of when activation in the sensory cortex can be seen, this is found at other instances as well but not to the extent that was expected.

Fig. 9 represents the activity of the channels that correspond to the sensory cortex. Here we do see activity, this activity is on the other hand present not only after but also before stimuli is applied. As there is significant activity pre-stimuli the activity after cannot be regarded as significant SEPs as they cannot be proven to have been provoked by the applied electrical stimuli. Fig. 1 better represents SEPs where the activity before stimulus is significantly lower than that of the after.

Fig. 10 represent the topographic plots of the spatial activation during different timeslots after stimulation. Here distinct SEPs were expected to be found but the experiment was as earlier mentioned unsuccessful in showing these. Even though some activities are seen in the sensory cortex, this cannot be regarded as SEPs as it is also seen in the time slot before the electrical stimulation which is represented by Fig. 11 As the activation is seen before the electrical stimulation it cannot be regarded to be a consequence of the stimulation.

Beyond the aspects of electrical interference, improper measurements and low quality equipment there could be some other factors limiting the quality of the recordings. Considering that the subject is expecting a stimulation this could affect the response [5]. Additionally, especially considering the first experiment, the subject had some difficulties sensing the stimulations as well as concentrating only on these which may have affected the quality of the data. In future testing higher quality equipment could be used with additional shielding as well a new protocol for testing.

Even though not getting significant results from the experiments was disappointing it is not unusual considering the time available for our involvement in contrast to the much larger magnitude of the project. It should be noted that two experiments are few in the context and that our work is only a small part of an area that will continue to grow and evolve.

A. *Ethics*

When conducting studies with test subjects the participants integrity is of great importance. Considering this the experiments started off with signing an agreement to give consent to the handling of the personal information.

Another thing worth discussing is sharing and ownership of the data. Researchers should clearly communicate to participants how their data will be used and whether it will be shared with other researchers or made publicly available. If data is shared, steps should be taken to protect the identity of participants.

B. *Sustainability*

In the accelerating development of using EEG in the scientific field it is important promote social impact and inclusivity. The EEG technology can contribute to social welfare, such as applications in healthcare and neurorehabilitation.

Another field connected to sustainability is energy efficiency. Focus on the development of energy-efficient EEG systems, and highlight research and innovations aimed at reducing power consumption in EEG devices and optimizing algorithms for signal processing. This is always important but especially if using wireless equipment in need of batteries. In this case the production of these batteries should be in such a manner that the environmental impact is as small as possible.

V. Conclusion

After performing and analyzing the two experiments of EEG recordings, no significant results can be found. The thesis to see activity in the sensory cortex of the brain in the opposite side of the body to a limb receiving electrical stimulation can

not be proven. It is difficult to explain why the project did not obtain any significant results. This project is part of a larger project researching neuroscience, which is a relatively unexplored field. With available knowledge, it can be stated that the collected EEG-recordings is of bad quality, which deems the collection of significant results impossible. We did not obtain any results but we obtained the skills for performing EEG data collections as well as for EEG and ERP processing analysis.

VI. Acknowledgement

We would like to express our heartfelt gratitude to our supervisor, Jia Liu, for her invaluable support and guidance throughout the course of this project. Her expertise, insightful feedback, and unwavering encouragement have been instrumental in shaping our research journey.

We would also like to extend our sincere appreciation to LTH for granting us access to their exceptional facilities, particularly the EEG lab. The availability of such resources has been crucial in conducting our experiments and obtaining our data.

Both Julius Cewers and Kalle Svensson have participated as subjects in different experiments during the course of the project. Both have been involved in the extraction of the data as well as the processing, which was done with the usage of code provided by Jia Liu. The report has been written by both Julius and Kalle, Julius mainly focusing on the introduction, discussion and conclusion while Kalle has been responsible for the method as well as the results. It is important to note though that the whole project has been a team effort and no part has been solely one person's responsibility, every part is built on thorough discussion and cooperation as well as frequent consultation by Jia Liu.

This project has truly been a collaborative effort, and we are immensely grateful for the contributions of everyone involved. We would like to thank Jia Liu once again for her mentorship and LTH for their generous support.

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APPENDIX

A. MATLAB Code

EEG-processing.m was given by our supervisor along with package with functions ready to use.

```
% Notch filter
Lowcut_fre=47;
Highcut_fre=50;
temp=eegfilt(EEG, fs,Lowcut_fre, Highcut_fre,0,1024,1,'firls');

% Bandpass filter
Lowcut_fre4=1;
Highcut_fre4=30;
EEG_cut=eegfilt(temp, fs,Lowcut_fre4, Highcut_fre4,0,1024,0,'fir1');

% Segmentation
pre_stimu=-0.2;
post_stimu=0.3;
Trials=zeros(length(chan_order),ceil((post_stimu-pre_stimu)*fs),length(found_p));
for i=1:length(found_p)
    Trials(:,:,i)=Data_ICA(:,found_p(i)-floor(-pre_stimu*fs):found_p(i)+floor(post_stimu*fs))
end
Evoked_data=mean(Trials,3);
% ERPs
figure
x=linspace(-200,300,0.5*fs);
subplot(3,2,1), plot(x,Evoked_data(25,:),'LineWidth',3), xlim([-50,200])
y_value=0.000600000000000000;
title('C5'), xlabel('Time(ms)'), ylabel('Amplitude(\muV)');
grid on
subplot(3,2,2), plot(x,Evoked_data(26,:),'LineWidth',3), xlim([-50,200])
title('C3'), xlabel('Time(ms)'), ylabel('Amplitude(\muV)');
grid on
subplot(3,2,3), plot(x,Evoked_data(28,:),'LineWidth',3), xlim([-50,200])
title('Cz'), xlabel('Time(ms)'), ylabel('Amplitude(\muV)');
grid on
subplot(3,2,4), plot(x,Evoked_data(30,:),'LineWidth',3), xlim([-50,200])
title('C4'), xlabel('Time(ms)'), ylabel('Amplitude(\muV)');
grid on
subplot(3,2,5), plot(x,Evoked_data(31,:),'LineWidth',3), xlim([-50,200])
title('C6'), xlabel('Time(ms)'), ylabel('Amplitude(\muV)');
grid on
start_point=floor((0.04-pre_stimu)*fs), end_point=floor((0.055-pre_stimu)*fs);
figure
topoplot(mean(Evoked_data(:,start_point:end_point),2),chanlocs)
colorbar('location','westoutside')
start_point=floor((0.02-pre_stimu)*fs), end_point=floor((0.03-pre_stimu)*fs);
figure
topoplot(mean(Evoked_data(:,start_point:end_point),2),chanlocs)
colorbar('location','westoutside')
start_point=floor((0.01-pre_stimu)*fs), end_point=floor((0.02-pre_stimu)*fs);
figure
topoplot(mean(Evoked_data(:,start_point:end_point),2),chanlocs)
colorbar('location','westoutside')
start_point=floor((-0.03-pre_stimu)*fs), end_point=floor((-0.02-pre_stimu)*fs);
figure
topoplot(mean(Evoked_data(:,start_point:end_point),2),chanlocs)
colorbar('location','westoutside')
```