Do Tripolar Concentric Ring Electrodes record Sensorimotor Rhythms better?

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DECLARATION

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

TIEN KHOA TANG

07/11/2021

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ABSTRACT

Sensorimotor rhythms (SMRs) were recorded over the sensorimotor cortex in the preparation, and during imagine or performing of an observed action. According to previous studies, it is used to implement classification in the Brain-Computer Interface with its spatial and spectral features. However, the majority of these studies were conducted using traditional electrodes. A new cutting-edge called the tripolar concentric ring electrode (tCRE) was developed based on approximating the surface Laplacian came from the idea of the nine-point difference method. It was expected to increase the spatial resolution as well as effectively reduce movement artefacts such as eye or limbs movement. Therefore, the ultimate goal of this project was to provide more evidence of the advantages and disadvantages of recording SMRs using tCRE. Three smaller goals have been done including designing and executing a proper experiment pilot, success in recording SMRs in different conditions, and finally plotting and exploring the event-related (de)synchronisation (ERD/ERS) relative to participant response. There are six participants' EEG data was recorded in four different conditions: hand tapping, imagine hand tapping, foot-tapping, and imagine foot tapping. 40 channels were recorded including 20 tCRE electrode channels and 20 traditional electrode channels. Raw data was cleaned by provided function from EEGLAB, reconstructed with principal component analysis to evaluate valuable data. Then, its spectrogram was calculated by using the continuous wavelet transform (CWT) with the frequency range 8-12 Hz to only remain SMRs. The ERD/ERS was calculated by normalising to the baseline for observing the decrease or increase trends. Unfortunately, the results from this project were not enough to conclude the main goal as both types of electrode shows the same performance in terms of ERD/ERS. Even though tCRE electrode showed an advantage in reducing noises, some of its channels were considered as bad channels and it show a worse performance when observing ERD. Overall, the approach of this project was proved as contributing an idea for assessment and there are spaces for further studies.

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INTRODUCTION

Overview

The Brain-Computer Interface (BCI) is an essential technology that allows patients with a neurological injury to communicate with their outer environment (Annen et al., 2018). Through the patient's different electrophysiological signals, a BCI system converts the user's brain signal into commands and perform tasks or controls assistive equipment such as a prosthesis, wheelchair or even speller system. In modalities such as EEG, MEG or ECoG, a synchronized brain signal called the sensorimotor rhythm (SMR) can appear in the cortex. After sensory input from the visual cortex, auditory cortex or even somatosensory cortex, the posterior parietal association cortex will send planned movement information to the dorsolateral prefrontal association cortex and at this time the SMR was formed.

SMRs are comprised of mu-rhythms (μ) with a frequency range from 8-12 Hz, (Chang et al., 2012) that is recorded over the central and posterior scalp locations. It occurs with both human actual movement and imagined movement (Neuper et al., 2006). Mu rhythms can be observed with attenuation in amplitude or an increase in amplitude that are called event-related desynchronization (ERD) and event-related synchronization (ERS) respectively.

There is a number of studies that explore the application of SMRs in BCI for disabilities, such as severe communication disorders (Kübler and Mattia, 2016). The study, conducted by Kübler and Mattia in 2016, used different types of input such as event-related potentials and sensorimotor rhythms. The results from applying SMRs demonstrated that severely paralysed patients can communicate and interact with thinking. According to the results of a study on SMR-based BCI, 20% of participants were not able to perform demanded control and 30% of others experienced a poor controlling capability. The authors concluded a further requirement of user training and improvement was needed (Sannelli et al., 2019). One possible improvement is to increase the quality of EEG data. This study hypothesises replacing traditional electrodes with tripolar concentric ring electrodes (tCRE) to improve the EEG recording process. Six healthy participants will be asked to watch prompt videos and perform imagined and actual movements. 20 tCRE electrodes placed over the motor and sensorimotor cortex in the scalp will record EEG. Participants' data will be then analysed by visualizing its ERD/ERS results. Comparisons will be made between tCRE and traditional EEG recordings, and between movement and imagined movement data.

Objective

I. Design and execute a proper experiment task that can be used as the presentation for recording SMRs.

II. Recording SMRs under a variety of different conditions such as hand movement and foot movement.

III. Compare the tripolar concentric ring electrode (tCRE) and traditional electrode performance between an imagined experiment and a movement experiment.

Thesis structure

There are five main parts written in this thesis including:

- Introduction: background information related to the definition of SMRs, how it was recorded through the human brain cortex. The objective of the thesis was also depicted in this part as well as the thesis structure.
- Literature review: information on the tCRE electrode and its previous research papers is reviewed. The advantages and disadvantages of using the tCRE electrode in recording EEG were described. Additionally, previous event-related desynchronization and event-related synchronization related papers are also indicated in this part as it would be the main part of the results part.
- Methodology: a brief description of designing experiment tasks and how they perform was one part of this section. A recording process is also shown with details about participants, issues before and during the recording happened. The analyzing process of SMRs data was then described in detail including problems that happened during the working time.
- Results and discussion: the event-related response results are visualized in figures and they are divided into two-part “Visual-Imagine task” and “Visual-Movement task”. An unexpected movement artefact was detected in both tCRE electrode data and traditional electrode data. The root of this issue is pointed out in the discussion part.
- Conclusion and future works: the conclusion related to the objective of this thesis was described in detail as well as the expectation of future works that can be done to improve the results of this study.

LITERATURE REVIEW

Overview

In this section, background knowledge and achievement of previous studies are reviewed and explored. Currently, studies recording sensorimotor rhythms are mostly done by using traditional electrodes. There is no evidence of using tripolar concentric ring electrodes that were reported to have advantages in SMRs recording.

The source of sensorimotor rhythms

When observing an action, a sensory input (visual signal) travels through a primary cortex, a secondary cortex and finally to an association cortex. In contrast, a motor output (movement) starts from the association cortex and travels in the opposite direction along the same pathway. Sensorimotor rhythms are recorded in the sensorimotor association cortex, of which there are two: posterior parietal association cortex (PPAC) and dorsolateral prefrontal association cortex (DPAC).

Figure removed due to copyright restriction

Figure 1. A diagram of the sensorimotor association cortices and pathways of transferring information (Paskari, 2007)

According to Figure 1, the posterior parietal association cortex receives input signals from the auditory cortex, visual cortex and somatosensory cortex. Integrated signals from the PPAC are sent to the dorsolateral prefrontal association cortex and then forwarded to the motor cortex. During this

receiving and sending process, SMRs can be recorded that represent the observed information (He et al., 1995).

Sensorimotor rhythms have the frequency range 8 – 12 Hz, and are also called μ rhythms. According to the source of SMR indicated in Figure 1, the three main brain regions that are the focus for SMRs are indicated as: the motor cortex (green), the sensorimotor cortex (yellow), and the primary visual cortex (red).

The tripolar concentric ring electrode and its benefits

Tripolar concentric ring electrodes were designed and developed by Walter G. Besio with the idea of improving EEG recording by approximately calculating a surface Laplacian directly in hardware. The surface Laplacian, also known as the scalp current density, is a method using mathematical algorithms to transform the EEG signals into approximates of radial current flow (Kayser and Tenke, 2015).

Starting with the idea of improving spatial resolution, the hypothesis of using a tripolar concentric rings configuration was developed by (Besio et al., 2006).

Additionally, Besio had explained his finding in (Besio et al., 2006). The tripolar concentric ring configuration indicated the advantage in greater attenuation with radial distance. It showed a noticeably enhanced accuracy after being estimated and localized by using the surface Laplacian. Furthermore, it was claimed that the signal to noise ratio of EEG recorded by using tCRE electrode (tEEG) was nearly four times that of the EEG recorded by using conventional EEG electrode (eEEG), as muscle artefact and low-frequency noises were effectively reduced (Aghaei-Lasboo et al., 2020, Koka and Besio, 2007).

According to the manual provided by CREmedical, the Impedance checking process of the tCRE electrode could be done yet consumed a lot of time as each of the output wires must be tested individually. Because of the limitation of participant time, the impedance checking process was not able to perform in this study. However, tCRE electrodes themselves was claimed to be able to cancel noises such as movement noise (Aghaei-Lasboo et al., 2020), so the checking process can be neglected.

Figure 2. One tCRE electrode, manufactured by (CREmedical)

As the result, using a tripolar concentric ring electrode, a sample of an electrode is illustrated in Figure 2, which is expected to have a good performance in this study. With its feature to clean muscle artefact by itself, sensorimotor rhythms collected from the movement task should not have movement artefact and give a clear observation of its trend.

Event-related desynchronization/synchronization

An event-related potential is a time-locked voltage/signal that is correlated with responding to an event. A decrease of power is known as an event-related desynchronization (ERD) which is produced, over the sensorimotor cortex areas, during the preparation, execution or even imagining of an observed movement (Neuper et al., 2006). After the preparation, execution or imagining has finished, over the same place, an increment of power, known as an event-related synchronization (ERS), can also be recorded (Toro et al., 1994).

According to a study conducted in 2021 and reviewed in (Stieger et al., 2021), ERD was used to assess the quality of EEG signals used for a BCI. The collected data was highpass filtered at 1 Hz to remove drifts, and bandpass filtered in the range of 8 - 14 Hz to observe the response (Stieger et al., 2021). The recorded data were also averaged among all trials. Then it was normalized to its baseline (the period from 1s before the stimulus to the time of the stimulus) and using the calculating method introduced by (Pfurtscheller, 2001) to calculate ERD/ERS. The results of this study show a strong ERD at C3 in the moving-up task, whereas a moderate ERD and a strong ERS were detected at the same location in the moving-down task. These results were also expected to achieve in my study and even better response when using the tCRE electrode.

METHODOLOGY

Experiment setup

Recording hardware

The recording process was performed by using the g.HIAMP bio amplifier. It is equipment invented by g.tec medical engineering and has the ability to simultaneously record up to 256 channels at 24-bit resolution. Due to the limited number of tCRE electrodes, 20 passive electrodes were plugged into the 64 channel passive electrode connector splitter box and played the role of collecting input signal for the g.HIAMP.

The electrode type used in this experiment was the tripolar concentric ring electrode (tCRE). It is a passive electrode, designed and manufactured by CREmedical. As illustrated in Figure 2 the figure below, there are three concentric rings on the surface of the electrode, enabling three local voltages to be detected. It was designed to be able to record both tEEG and an emulation that is equivalent to the conventional EEG (eEEG). So each tCRE electrode will give two output voltages. The 20 tCRE electrodes are connected to the t-interface box, Figure 3, and the 40 output signals are connected to a traditional EEG headbox via a ribbon cable. The headbox also requires one passive reference electrode and one passive ground electrode.

Figure removed due to copyright restriction

Figure 3. tCRE headbox with 20 tCRE electrode (CREmedical).

Two computers, one inside and oneoutside of the Faraday Cage, control the recording process while all other equipment is positioned inside. The presentation computer in the cage is an all-in-one, and has a duplicating screen outside the cage. It was used to present the presentation during the recording process. Another computer, outside of the cage, has the ability to record SMRs. The acquired data is collected from the g.HIAMP and streamed between the computer on a static network via the Lab Streaming Layer (LSL) protocol. By connecting to the LSL stream, the recording computer collects the acquired data from the stream and stores it on the hard drive using the Labrecorder program.

Additionally, programmed functions in MATLAB can also collect the recorded data and display it for monitoring in real-time.

Recording software

After setting up g.HIAMP, tCRE, and splitter box, a configuration file must be written so that Labrecorder can read and record the signals from each electrode correctly. There are 41 channels in total, consisting of 20 tCRE signals, 20 emulated EEG signals, and 1 reference signal. Therefore, the configuration file must have 41 signals specified, each with the following properties:

- Reference electrode: FCz
- Sampling rate: 1.2 kHz
- Label: channel's label

The configuration file was written by using provided the "`generate_cfg.m`" function in MATLAB and will be loaded before each recording session. During the session, participants were expected to observe and listen to the presentation that is played on the screen and speakers. It was designed as a set of actions that the participant is expected to follow. The presentation code was written in python and run by the PyCharm program.

Experiment design

Tasks design

Pilot ideas

The aim of the study was to explore the brain responses of the participant when executing (copying) or imagining executing the actions observed in the prompt video. So, the main aim of the task design was to design a single video showing a movement that is familiar and similar to normal human action. Previous studies used tasks where the participant had to imagine controlling a virtual helicopter by navigating a quadcopter, in virtual space, to go safely past a ring (LaFleur et al., 2013). The participant was required to think of doing 3D motions including up, down, forward, and backward. The spectral and spatial properties of the resultant SMR were then studied to classify the type of imagined action, such as a move to the left, a move to the right or even translation movements.

These studies demonstrate that thinking of an action or seeing an action can affect SMRs. Therefore, a simple action is a good starting point for my study. Many pilot videos were recorded and considered as sample videos:

A. Flexion of both hands (first pilot, video length 10s)
B. Flexion of a single hand (first pilot, video length 10s)
C. Walking (first pilot, video length 10s)
D. Driving car (first pilot, video length 10s)
E. Hand Tapping without a synchronising guide (second pilot, video length 20s)
F. Foot tapping without a synchronising guide (second pilot, video length 20s)
G. Hand tapping with a synchronising guide (third pilot, video length 20s)
H. Foot tapping with a synchronising guide (third pilot, video length 20s)

The structure of the pilot was also varied such as:

1. There was one main recording session including two parts. The first part started with instruction for the participant, then video A and video B were played randomly 10 times in total (hands movement). Between the two parts, there was also instruction indicating the end of the first part and the start of the second part. In the second part, video C and video D were also played 10 times in total (complex movement). The total time for the session was 6 minutes including reading instruction time and playing video time. Diagram 1 indicates the structure for the first pilot.

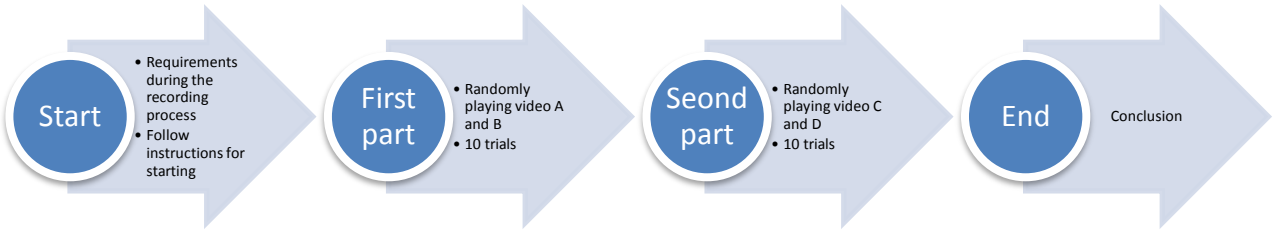

Diagram 1. The structure of the first pilot

2. There were two main recording session, a visual movement session (VMS) and a visual imagine session (VIS), where each session included two parts. Both sessions' presentation was technically the same, but the participant was required to copy the observed actions in the VMS and only imagine the observed actions in the VIS. In each of the sessions, there were two parts. The first part started with instructions for the participant, and then video E was played 30 times. Between the two parts, there were also instruction indicating the end of the first part and the start of the second part. In the second part, video F was played 30 times. The total time for the

both session was nearly 22 minutes including reading instruction time and playing video time. Diagram 2 indicates the structure of the second pilot.

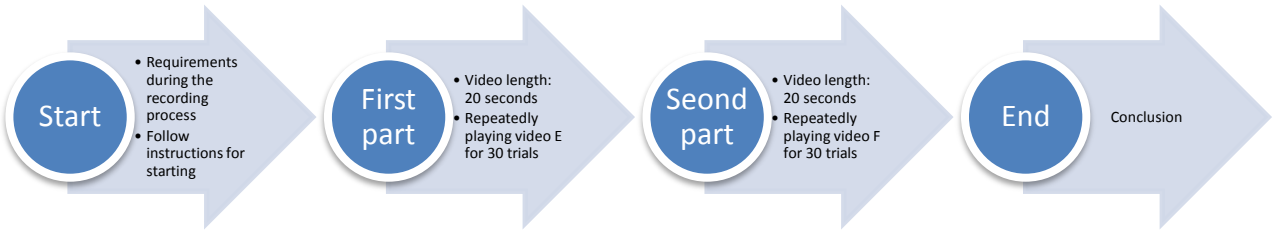

Diagram 2. The structure of the second pilot

3. The third version of the pilot was similar to the second pilot excluding the structure of video and using video G and H instead of video E and F respectively. The idea of using a synchronised repeating action came from using the mirror neuron cortex of the human brain. In a study conducted in 1996 and 2005 (Gallese et al., 1996, Ferrari et al., 2005), the mirror neuron was activated by both observing and performing actions and the response was stronger when actions were performed in synchrony. As a result, the hand tapping video was remade to have 18 tapping actions in 14 seconds. Additionally, based on the theory used to calculate the ERD/ERS described in the Literature review, the first 3 seconds of the video were filmed without any action and labelled as the "First resting phase" or the baseline. Meanwhile, the last 3 seconds were also named "Second resting phase" and used to observe the ERS. Diagram 3 indicates the structure of the third pilot.

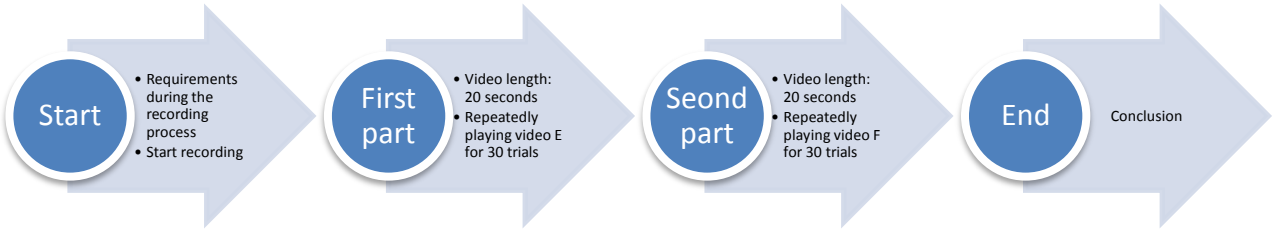

Diagram 3. The structure of the third pilot

Pilot decision matrix

Table 1. Decision matrix for choosing suitable action videos from 7 pilot videos A, B, C, D, E, F, G, H. There were 4 criteria that were taken into consideration: ERD/ERS, engagement of participants, data quality (minimum artefact) and the consistency of the presentation

Weight	Criteria	A	B	C	D	E	F	G	H
30%	ERD/ERS	6	6	6	5	7	7	8	8
20%	Engagement	8	8	6	6	6	6	5	5
25%	Data quality	7	7	7	7	8	8	8	8
25%	Consistency	6	6	6	6	7	7	7	7
	Total	6.65	6.65	6.25	5.95	7.05	7.05	7.15	7.15

To be more specific, videos type A, B, C, D belonged to the first experiment version while E, F were used in the second version, and G, H were presented in the third version. According to Table 1, among four categories that were taken into consideration, A and B stand out as having the highest weight in "engagement" as they were designed to be the same as a normal action and only being played in a short time.

Comparing the second and third pilots' videos, the third pilot was more boring according to 6 participants' feedback after taking part in the experiment. Only one 20 second length video played 30 times in each part was a challenge for staying awake, but its result showed a good difference in ERD and ERS. Meanwhile, the ERD/ERS status of the data had a stronger weight in making the final decision. Based on the total point, videos G and H were chosen to be used in the presentation with a score of 7.15.

Table 2. Decision-making matrix for choosing a suitable structure from three different pilots. Five different criteria were taken into consideration for the final decision. The total score was calculated as the summation of the observation point multiplied by the criteria weight.

Weight	Criteria	First pilot	Second pilot	Third pilot
20%	**Consistency**	7	8	8
30%	**Number of Trials**	5	7	8
10%	**Less Preparation Time**	7	7	7
30%	**ERD/ERS**	5	6	8
10%	**Engagement**	7	5	5
	Total	**5.8**	**6.7**	**7.6**

Comparing between the three pilots, the first pilot had the advantage of higher engagement with a score of 7 while the other two only got 5. Randomizing the video playing order attracted participants' attention and resulted in not feeling distracted and/or sleepy. Even though that was a good point, the "engagement" weight was just 10% compared to the other categories. Number of trials and ERD/ERS results shared the same weight at 30% each and became the top priority in choosing a proper recording method.

Comparing the second and third pilot, the only difference was that the third pilot's videos were redesigned to have a more specific action. In videos G and H, the recorded actions were basic actions, such as left-hand tapping and feet tapping, and they were performed repetitively. The synchronised action would trigger the mirror cortex to generate a good response in the sensorimotor cortex. As a result, the ERD/ERS achieved from the data of the third pilot, which will be shown in Results, showed a more noticeable decreasing trend in the responding phase (ERD) and an increasing trend (ERS) in the last resting phase.

Although the final version was less engaging according to the participant's feedback, its advantages in statistical meaning and ERD/ERS results gave it the highest score at 7.6 in totals and it become the choice for use in the experiment.

Final tasks

Two tasks had been designed and used for this study such as the Visual_Imagine task and the Visual_Movement task. They both shared the same presentation structure illustrated in Diagram 4:

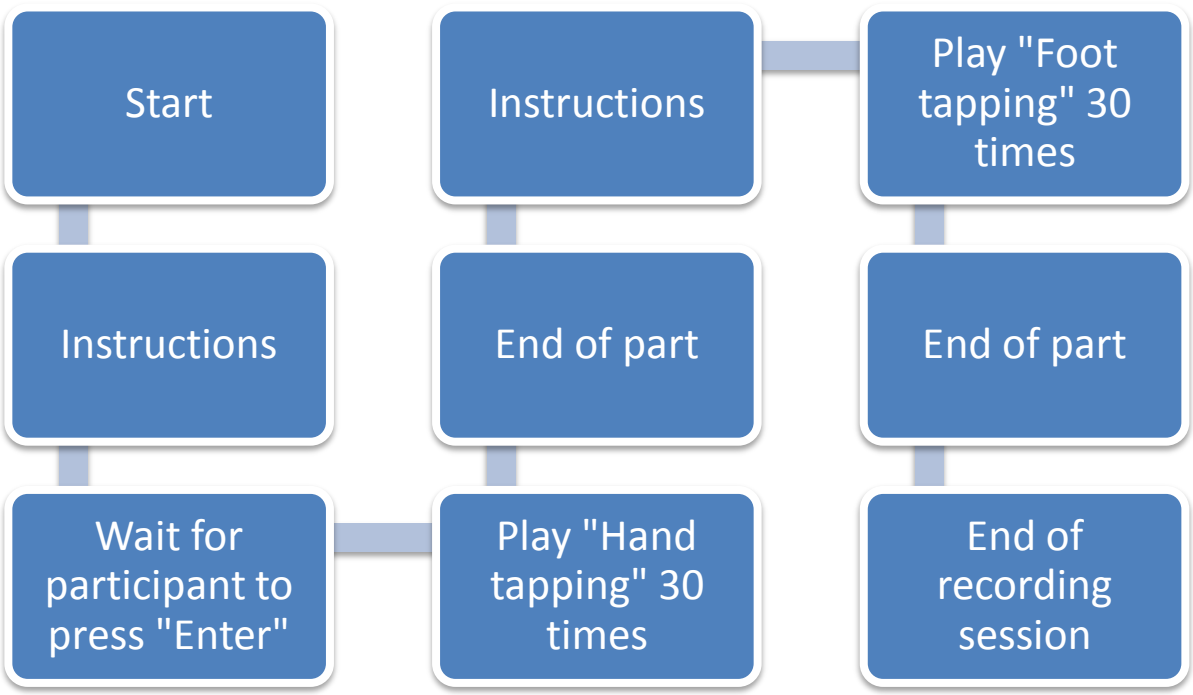

Diagram 4. The structure of the recording task. This structure was used for both tasks (imagined and actual movement).

The only difference between the two tasks was that the movement task required the participant to actually perform the observed actions, while the imagine task requirement was only to observe and imagine. The purpose of the difference was to explore their ERD/ERS performance with and without movement artifacts.

To facilitate the data reading process, both the movement and imagine task structures were redesigned with unique SNAP markers, created by the LabRecorder for indicating a specific event. The video length was 20 seconds including 3 seconds for the first resting phase, 14 seconds for the responding phase, and 3 seconds for the last resting phase. Time “0” was set at the beginning of the first resting phase, resulting in “20” at the end of the last resting phase. The detailed structure can be found indicated in the Appendix A: Experiment structure.

Movement task important markers:

- In the “Hand tapping” part, 30 trials were conducted, each of them was marked with a marker “25” at time “0” and “35” at time “20”

- In the “Foot tapping” part, 30 trials were conducted, each of them was marked with a marker “28” at time “0” and “38” at time “20”

Imagine task important markers:

- In the “Hand tapping” part, 30 trials were conducted, each of them was marked with a marker “25” at time “0” and “35” at time “20”
- In the “Foot tapping” part, 30 trials were conducted, each of them was marked with a marker “28” at time “0” and “38” at time “20”

Recording process

Pre-recording

The pre-preparation process proceeded for all participants used the following instructions:

- The participant was asked to clean their head with the alcohol-filled multi prep, especially in the three regions of the motor cortex, the sensorimotor cortex and the primary visual cortex
- Locate the middle position of the participant’s scalp, known as “Cz”, and put on the electrode holder cap. The cap should be tight enough fit the participant's head snugly but not cause them to feel uncomfortable
- Turn on the related equipment such as g.HIAMP and t-interface
- Put tCRE electrodes in according to the 10-20 system as illustrated in Figure 4. To do so, start with filling the desired electrode holder with the TD 246 gel. Cover the tCRE electrode with a bit of the TD 246 gel and insert it in the cap .

Figure removed due to copyright restriction

Figure 4 The international 10-20 system electrode locations (Oxley, 2017) with three regions highlighted: the motor cortex electrodes (green), the sensorimotor cortex electrodes (yellow), and the primary visual cortex electrodes (red).

Figure 5 shows the outcome after placing all 20 tCRE electrodes into the cap.

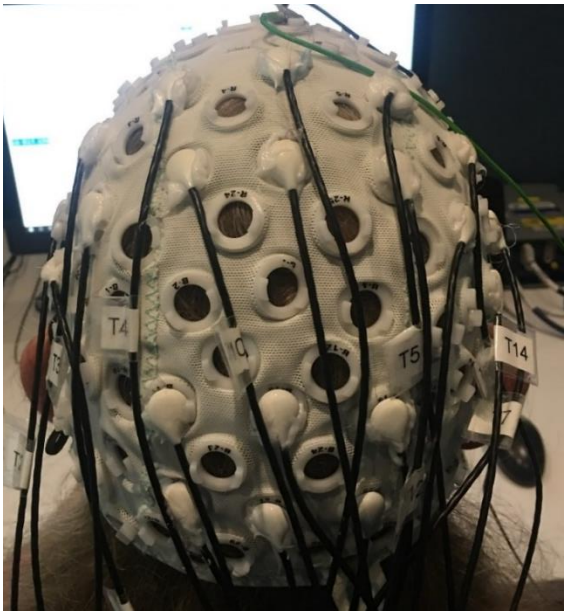

Figure 5. An example of the result of the preparation process. A participant was wearing a cap holder with 20 tCRE electrodes positioned in three different regions: the motor cortex (the first horizontal electrode line on the top), the sensorimotor cortex (the second horizontal electrode line), and the primary visual cortex (last two electrode lines). The green wire is the reference electrode which was placed in the "FCz" position, and the black wire at the far top was the ground electrode position in the "FPz".

Recording process

The experiment was performed in the Faraday cage and controlled by an outside computer. The recording process was controlled by a program call LabRecorder that has the ability to start the presentation and record EEG data from the LSL stream.

There were four tasks in total as the eye open baseline (EO_baseline), the eye close baseline (EC_baseline), the Visual_Imagine task, and the Visual_Movement task. The recording session started

with running the EO_baseline and EC_baseline for checking the current status of the participant and all equipment. Then the main recording part was done by lauching both the Visual_Imagine task, and the Visual_Movement task in turn. In the end, participant would be helped to take the cap off and had their hair cleaned.

Analysing data

Reading and analysing the EEG data from the experiments had been done by using MATLAB and two toolboxes: the EEG3 toolbox and the EEGlab toolbox. Detailed code is added in the Appendix C: MATLAB code. The analyzing process is depicted in Diagram 5:

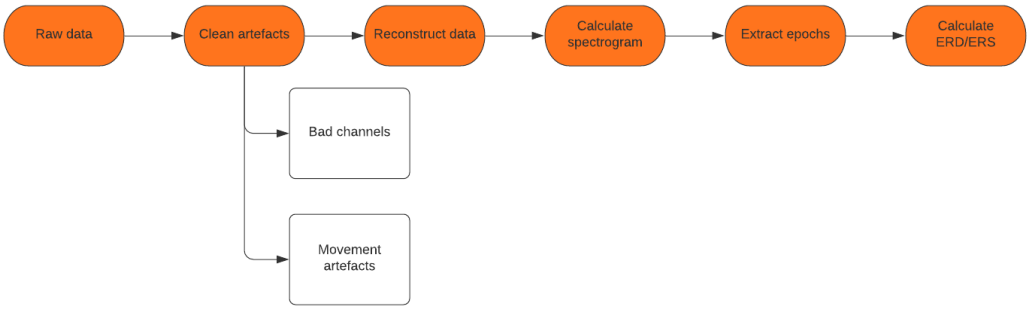

Diagram 5. Loading and processing EEG data diagram.

The analysing process had 6 stages including:

- Load up raw EEG data using the "`load_SMRs.m`" function
- Clean artefacts using the "`clean_EEG.m`" function
- Reconstruct data using Principal Components Analysis (PCA)
- Calculate spectrogram using the continuous wavelet transform (CWT) at frequency range 8 - 12 Hz
- Extract epochs using the "`extractepochs.m`" function from the eeg3 toolbox
- Calculate and plot ERD/ERS using the "`relbaseline.m`" and "`plot`" function from the eeg3 toolbox

All functions mentioned above are explored in more detail in the following text.

Load up raw data

The "`load_SMRs.m`" function was designed to load up raw EEG data in "`.xdf`" format. It required two inputs, the "participant" and "task", which were the currently working participant and the target task. Since we are working with tCRE electrodes, there were 41 channels received including 20 tCRE

electrodes data, 20 emulated electrodes data and 1 reference electrode data. All of these data have the same electrode type as it was the default format. Therefore, distinguishing between tCRE EEG and emulated EEG had been done by:

- Finding tCRE channels by testing whether its label starts w ith a “t” or not
- If the result was true, then that electrode type would be set as “tCRE”
- According to the manufacturer, tCRE data was scaled down by 187

Clean artefacts and reconstruct data

The cleaning process was done by using a function called “`clean_artefact.m`” in EEGLAB. This built-in function can remove flatline channels, low-frequency drifts and noisy channels. It required an EEGLAB dataset structure as an input, such that input data is continuous EEG data including channel locations, channel labels, events, times, and data.

First bad channels by calculating bad channel were detected correlation. A channel was marked as a bad channel when its correlation to the neighbour channel was lower than 80%. EEG signals collected from a set of local electrodes should be similar to each other. When the correlation was lower than 80%, the collected data had a large variation, and that channel could have been affected. The reason could be a large impedance and a lack of gel. Unfortunately, the impedance checking could not be performed before starting the recording session as there are not sufficient time and a lack of equipment. After applying the “`clean_artefact.m`” function for four tasks and averaging among six participants, several tCRE bad channels were detected and the results were depicted in Table 3.

Table 3. The number of channels collected by using tCRE electrodes before and after using clean artefact in four different tasks

	Hand tapping	**Imagine hand tapping**	**Foot tapping**	**Imagine foot tapping**
Pre cleaned	19	19	19	19
Post cleaned	13	10	13	12

Meanwhile, the number of bad channels, before and after being cleaned, in the eEEG data set was 0 for all four tasks. According to the study conducted by Besio, reviewed in (Besio et al., 2006)), approximating the surface Laplacian means that tCRE electrodes should be more sensitive to local signals, and to high-frequency noise. In the “`clean_artefact.m`” function, one of the criteria to

determine a bad channel was its correlation to its neighbouring channels is lower than 80%. The output data from tCRE electrodes would have more of a difference than traditional EEG channels, which may explain the removal of some of the tCRE channels.

After cleaning all bad channels, signals collected from tCRE and traditional electrodes were being analyzed and reconstructed by using Principal of Component Analysis (PCA). PCA is a statistical algorithm transforming multidimensional data to fewer dimensions to optimize the variation of the data (Pandey et al., 2011). Two outputs of this algorithm that were taken into consideration were:

- "Coeff": a matrix of coefficients for each principal component sorted in descending order of variation
- "Score": the representation of each observation in the principal component matrix

Multiplying the "coeff" matrix with the "score" matrix is the same as multiplying the matrix of high variation data to its score and results in a new set of valuable data. This step could also reduce signals which were noises or uncommon movement artefacts, as seen in Figure 6.

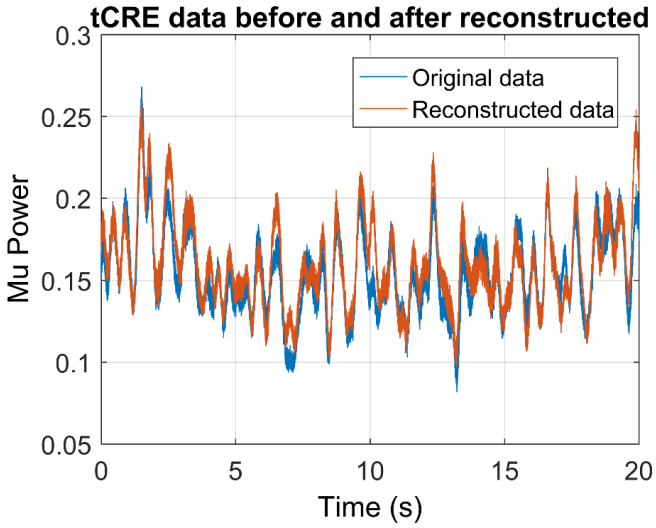

Figure 6. An example of tCRE data in two cases: before and after being reconstructed using PCA.

According to Figure 6, the red line is the reconstructed data while the blue line is the original data. Across 20 seconds, high-frequency noises were reduced.

Calculate ERD/ERS

After removing low correlation bad channels and high-frequency noise, each channel of the reconstructed data was used to calculate its spectrogram. A continuous wavelet transform in the frequency range 8 Hz -12 Hz was applied. This involved comparing the input signal to a defined wavelet

and recording the correlation at different times and scales In the provided "`cwt.m`" code, input data was put in the "`tfcwt.m`" function with the chosen frequency range and the complex Morlet wavelet with 3 Hz bandwidth and 1 Hz wavelet centre frequency. The results of this process were depicted by three axes:

- The X-axis indicates the translation of the standard wavelet function. In this case, it will be the duration of each trial
- The Y-axis indicates the dilation of the spectrogram. In this case, it has a range of 8 Hz – 12 Hz. This frequency range was chosen as this study only focuses on that band and it saved a lot of time for calculating the spectrogram
- The Z-axis indicates the coefficient between the input data and the standard wavelet function. Each block should have a colour indicating a different coefficient

After that process, the spectrogram data was then used to calculate its power over time by using the "`meanfreq.m`" function. By stage, our data was transformed into a time-frequency format across trial would have its frequency power. Therefore, to access only the meaningful portion of the trials, each trial must be extracted. These are also known as epochs.

To do so, a built-in function called "`extractepochs.m`" was used. According to the Appendix A: Experiment structure, the trigger signal generation box created a specific marker to define the start of each part of the recording process. A summary of the marker labels is indicated in Table 4

Table 4. The summary table of commonly used markers

	Marker	**Movement task**	**Imagine task**
Hand tapping	**Start**	**"25"**	**"45"**
	End	"35"	"55"
Foot tapping	**Start**	**"28"**	**"48"**
	End	"38"	"58"

The "`extractepochs.m`" function is able to look for a specified marker or markers, in this case the bolded markers in Table 4, and extract the desired start time and end time offsets, in this case -0.5 seconds and 20.5 seconds respectively. By doing this, each event marked with the given marker would

be cut out at 0.5 seconds before its beginning and 0.5 seconds after its end (trial length was 20 seconds).

Each epoch had its data normalized to the power of the first resting phase (first 3 seconds) by using the "`relbaseline.m`" function to manage variation between particpants. Then all epochs were averaged to retain only the most valuable data. At this point, there was only one remaining epoch, for each participant and for each task, and its data could depict the power change correlated to participants response.

RESULTS AND DISCUSSION

Results

The Visual - Imagine experiment

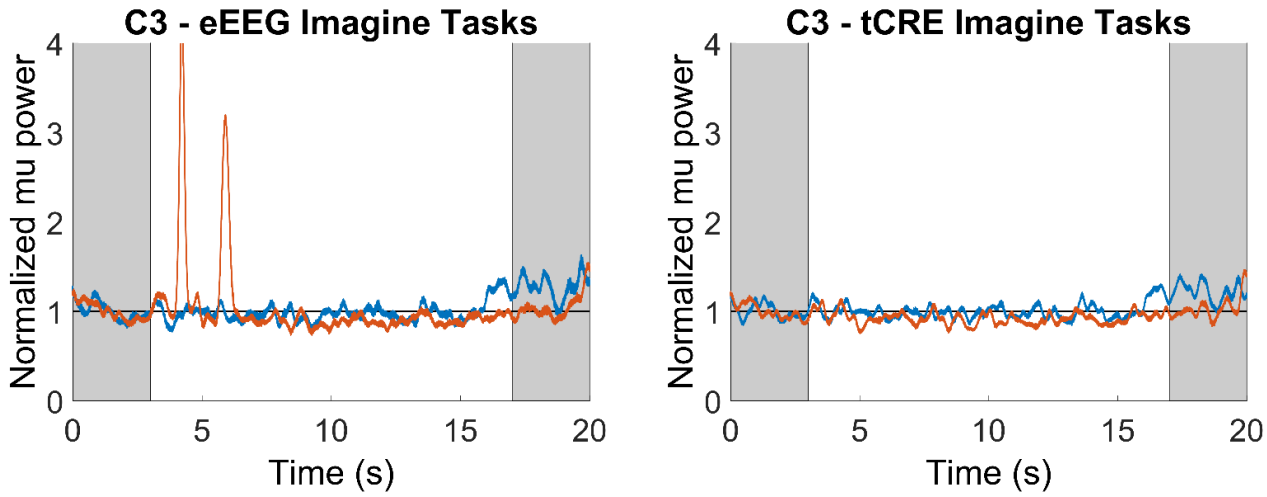

Figure 7. Results of imagine tasks were achieved from the emulated electrode (left figure) and the tCRE electrode (right figure) in channel C3 with averaging among six participants. Both lines showed moderate downward trends in the responding phase, also known as ERD, and followed up with an increment in the second resting phase, also known as ERS. The blue line indicates data acquired from the "Hand tapping task", the red line indicates data acquired from the "Foot tapping task" and the black horizontal line at 1 in Y-axes indicates the baseline for the response. Two grey regions are the resting phase while the white middle region is the responding phase starting from the 3rd second and ending at the 17th second.

The Visual – Movement experiment

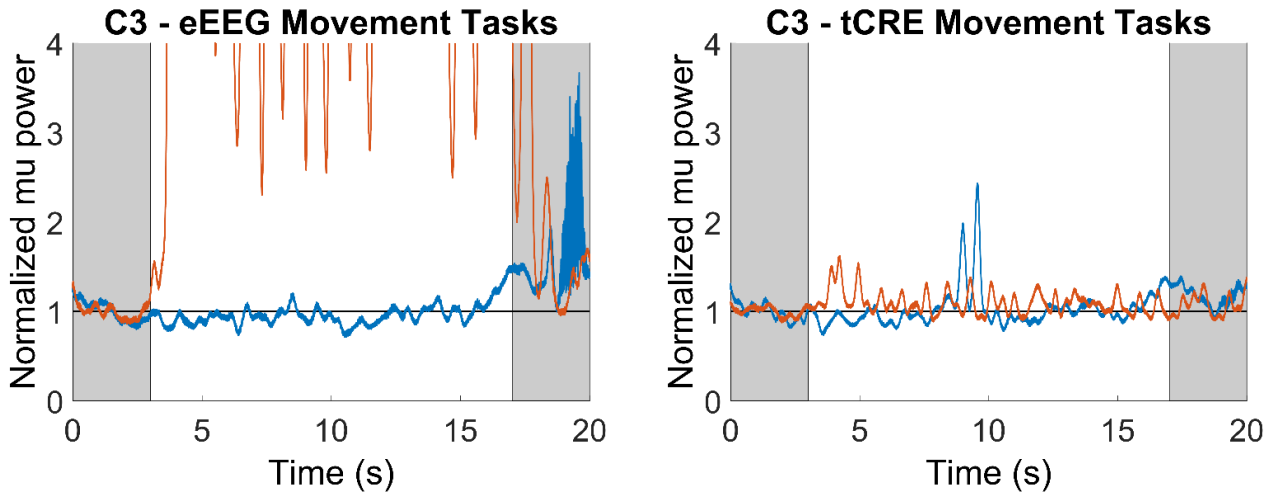

Figure 8. Results of movement tasks were achieved from the emulated electrode (left) and the tCRE electrode (right) in channel C3 with averaging among six participants. Blue lines showed moderate downward trends in the responding phase, also known as ERD, and with an increment in the second resting phase, also known as ERS. The blue line indicates data acquired from the "Hand tapping task", the red line indicates data acquired from the "Foot tapping task" and the black horizontal line at 1 in Y-axes indicates the baseline for the response. Two grey regions are the resting phase while the white middle region is the responding phase starting from the 3rd second and ending at the 17th second.

Discussion

Event-related desynchronization and event-related synchronization

The classification of human actions by using ERD/ERS had been applied in some previous studies. Additionally, a study conducted in 2021 (Stieger et al., 2021) had also explored sensorimotor rhythms for the same purpose. Stieger experiments were to distinguish between moving the cursor to the left or the right by imagining to open participants hand such that:

- Move the cursor left: imagine opening and closing left hand
- Move the cursor right: imagine opening and closing right hand
- Move the cursor up: imagine opening and closing both hands
- Move the cursor down: relaxe

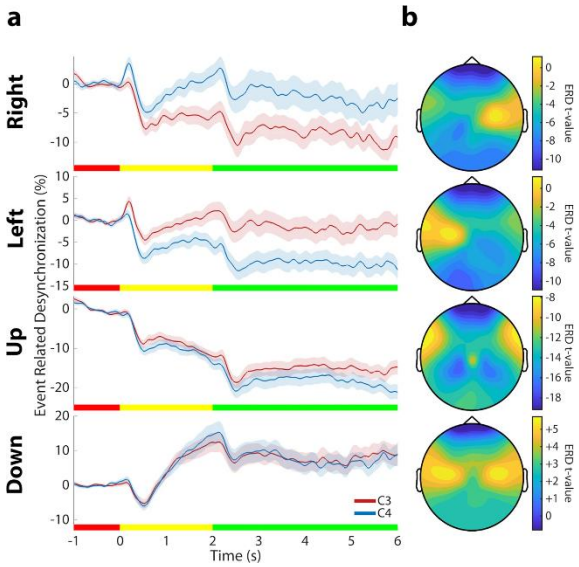

Figure 9. Event-related desynchronization (ERD) observation in the left-hand movement (C3 channel – redline) and the right-hand movement (C4 channel - blueline). ERD was relative to the baseline period (-1s to 0s – coloured in red in Time axes) (Stieger et al., 2021).

The results from my experiment are illustrated in Figure 7 shows nearly the same response for the left-hand experiment. In the responding phase, a downward trend indicating ERD was recognized which is expected to happen. As the right brain controls the left hand Figure 9 shows a stronger decrease in the C4 channel (the blue line). Unfortunately, due to the fact that the C4 channel was considered a bad channel during the cleaning artefact process in my study, we cannot observe the change in this region.

In terms of the “Foot tapping” in my project, illustrated as a red line in Figure 7 and Figure 8, my results show a similar response as Stieger achieved, in Figure 9. The power fluctuates a little while overall a decreasing trend in the responding phase was observed. This is easier to see in the Imagine task. This

means that a horizontal movement was performed by a combination of both hemispheres in the motor cortex.

According to my project results illustrated in both experiments, SMRs recorded with tCRE electrodes show an advantage of less low-frequency artefacts. Comparing both types of electrodes, low-frequency noises are able to be observed and captured with a higher amplitude in the emulated EEG results. In the eEEG "Imagine tasks", two high power peaks were captured and numbers of them have also been recorded in the eEEG "Movement tasks". As the number of high power peaks was nearly the same as the number of tapping feet, the movement is the likely source of this artefact. During the actual performing "Foot tapping", the tapping movement was affecting the balance of the participant's head. A small displacement between the scalp and tCRE electrodes would create motions artefact seen in the recorded data.

In terms of the tripolar concentric ring electrode, approximate the surface Laplacian which has the ability to reduce movement artefact as it is more sensitive to local signals. So tCRE electrode should have a good performance when it comes to low-frequency noise. Furthermore, in terms of averaging ERD power across time, the results from tCRE electrodes show a different performance compared to conventional electrodes even though tEEG and eEEG were both collected from one physical electrode.

According to Figure 10, although the results acquired from tCRE electrodes have less high frequency noise (thinner line), its averaged value over 2s, from 4s to 6s, is calculated as 0.93 (μV^2/Hz) while it is 0.91 (μV^2/Hz) for conventional electrodes. With the same calculation but on a wider time scale, all 14s of the responding phase, the averaged power was calculated as 1.02 (μV^2/Hz) (considered as no ERD) and 0.96 (μV^2/Hz) for tCRE electrode and eEEG respectively.

Additionally, the tCRE electrode had performed strangely in some periods such as at the 5.25 -5.75s in Figure 10. The two continuous peaks are larger in tCRE, as illustrated in the right plot Its cause is not clear, and has not been observed in any previous studies.

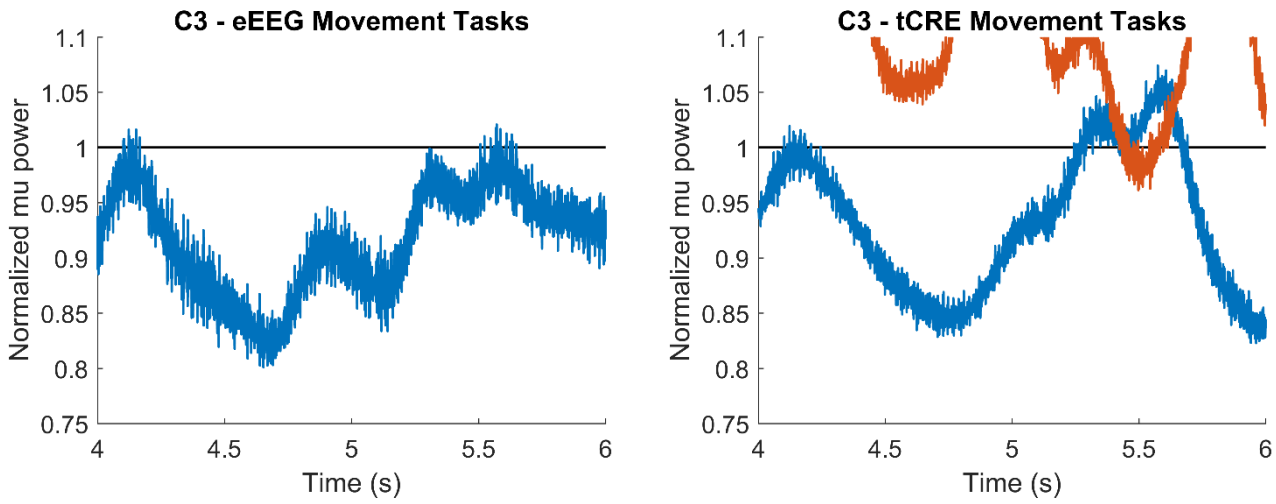

Figure 10. The results of ERD in Movement tasks that were zoomed in on: Time: 4s – 6s and Power: 0.75 to 1.1 (µV^2/Hz)

Artefact

In the processing and analysis stages of this project, some methods to reduce artefacts, such as random movements or intended movements, did not performed as expected. At the very beginning, reconstructing data using PCA was an acceptable attempt that removed some artefact as illustrated in Figure 6. Then the clean artefacs function from EEGLAB was used to try to remove frequency-related and movement-related noises. Along with cleaning movement noises such as eye blinkings, some of the tCRE channels were considered as bad channels and were removed. This action was made based on the correlation method developed by EEGLAB. As the result, we lost the “C4” channel which is a very important observation in exploring SMRs. A more careful approach to managing artefact removal may improve the results and perhaps allow C4 to be retained. More figures of the data is included in the Appendix B: Results.

CONCLUSION AND FUTURE WORK

Conclusion

In terms of the project objectives, some achievements and difficulties happened during this project. The positive and the negative sides could be seen according to the achieved goals such that:

- Design and execute a proper experiment task that can be used as the presentation for recording SMRs. There are 8 video genres and 3 experiment paradigms had been developed in total. However, after being considered across all criteria, only 2 stimuli videos and 1 paradigm were chosen for their most suitable and contribution to the project
- Recording SMRs under a variety of different conditions such as hand movement and foot movement. Based on the chosen paradigm, experiments had been done and SMRs were successfully recorded from 6 participants. The recording process was performed with 19 good tCRE electrodes and 1 tCRE electrode was determined as broken
- Comparing the tripolar concentric ring electrode (tCRE) and traditional electrode performance between an imagined experiment and a movement experiment. From the results of this project, the appearance of ERD/ERS was studied, and observing themselves gave a deeper understanding and the thrill for further research

The performance of tCRE electrodes was proved to be better in some conditions such as high-frequency noise cancellation and distal movement noises cancellation. However, it was still being affected by local noises such as minor motions between participant scalp and electrode. Furthermore, according to Figure 7 and Figure 8, there is no evidence for concluding that tCRE electrode was better than emulated electrode in the case of comparing ERD/ERS. The decreasing or increasing trends were not clearly illustrated in those figures, see more results in the Appendix B: Results.

This project has been done with some limitations of the hardware. Checking electrode impedance was an essential and standard practice with EEG but it could not be performed before any recording process. The limitation of tCRE electrode was impossible to perform a real-time impedance checking for every electrode at once. It was only able to check impedance for one output channel at a time while other electrodes must be turned off and disconnected. With the limitation of participant time, the checking process was unable to be done and results in unpredictable electrodes impedance. Even though tCRE electrode was able to cancel noise itself, the results for ERD/ERS was still not acceptable

and, therefore, unable to conclude the advantages of tCRE electrode in recording sensorimotor rhythms.

Future work

Despite many attempts that had been performed in this project, some goals had been achieved. There are more spaces to improve in this study and hopefully, a better outcome could be seen:

1. Improving the SMR recording paradigm by focusing on exploring ERD/ERS. A shorter and consistent version of video could be an important option, such that only have mono and more specific action as moving to one side only
2. Randomized playing video in the presentation for challenging participants to put more effort into responding. Additionally, increasing the number of trials would be a good way to record a more valuable response
3. Improving the artefact removing by using a better noises removal function such as independent component analysis algorithm (ICA) for isolating each hidden factor and remove the noises
4. Developing a method to check the impedance of all tCRE electrodes before recording
5. Using more tCRE electrodes to at least 64 electrodes to acquire and observe the changing of participant sensorimotor rhythms over the scalp. Meanwhile, reperforming the recording process with the separated traditional electrode so that both results do not come from one electrode source
6. Recording SMR with a more different type of actions such as finger movements, right-hand movements, limb movements, and other parts of human body movements. A wider range of movements could result in a deeper understanding of ERD/ERS performance whether they could be different in a different action
7. Comparing in different criteria and applying statistic test for more evidence
8. Obtain ethics approval and record SMRs from more participants

These suggestions of future works are huge and required working with CREmedical and other experts such as neurologists, IT, or even electrical engineers. Their expertise would provide a better chance for further study. Although there is some evidence to say that tCRE electrode is better for a specific condition, the main question is remained and is still not able to be fully answered. Nevertheless, the methodology used in this project is proven to be useful with spaces that can be improved.

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APPENDICES

Appendix A: Experiment structure

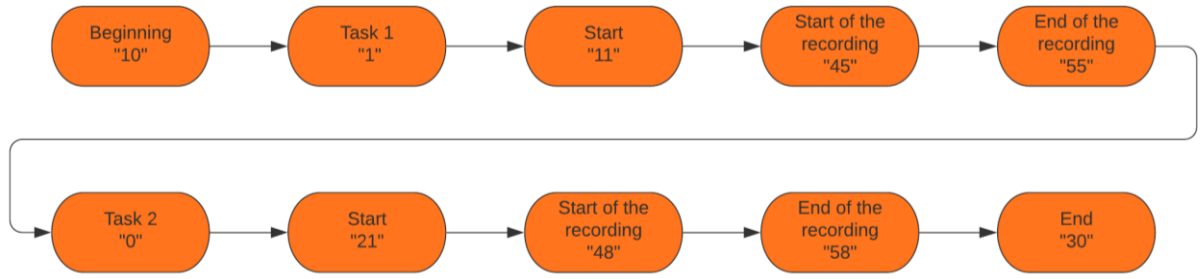

Figure 11. The flowchart describes the structure of Visual-Imagine task.

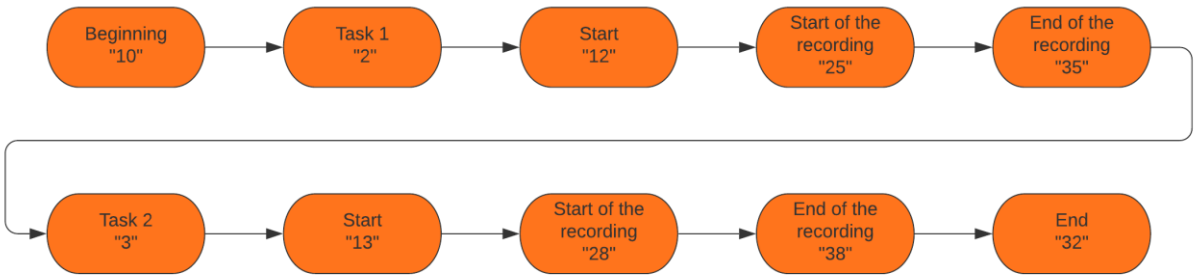

Figure 12. The flowchart describes the structure of Visual-Movement task.

Both Visual-Imagine task and Visual-Movement task was designed to play two prepared video “Hand tapping” and “Foot tapping”. According to Figure 11 and Figure 12, each step was marked with an marker, such as:

- Marker “10”: the beginning of the task
- Markers “30” or “32”: the end of the task
- Markers “0”, “1”, “2”, “3”: the start of recording of task
- Markers “11”, ”21”: the start of the recording of “Hand tapping” and “Foot tapping” in the imagine experiment, respectively. At this point, the instruction will be played on the screen, containing suggestion to relax and requirements to perform or imagine
- Markers “12”, ”13”: the start of the recording of “Hand tapping” and “Foot tapping” in the movement experiment, respectively. At this point, the instruction will be played on the screen, containing suggestion to relax and requirements to perform or imagine

- Markers “45”, “55” or “25”, “35”: the beginning and the end of the “Hand tapping” video
- Markers “48”, “58” or “28”, “38”: the beginning and the end of the “Foot tapping” video
- Markers “32”, “31”: the end of the recording process

These markers were designed for user to extract epochs at a specific time. For example, if I only want to extract all the recording process of “Hand tapping” task in movement experiment, I would do extracting epoch with the marker “25” for the beginning and “35” for the end. As the results, MATLAB would seeked and sliced the time period between those chosen markers.

Appendix B: Results

By limitation of the number of pages, the results for other channels were not added in the main part. So in this appendix, more results will be shown. All of these ploting used the same legends as what shown in the Results section, the blue line indicates data acquired from the “Hand tapping” task, the red line indicates data acquired from the “Foot tapping” task.

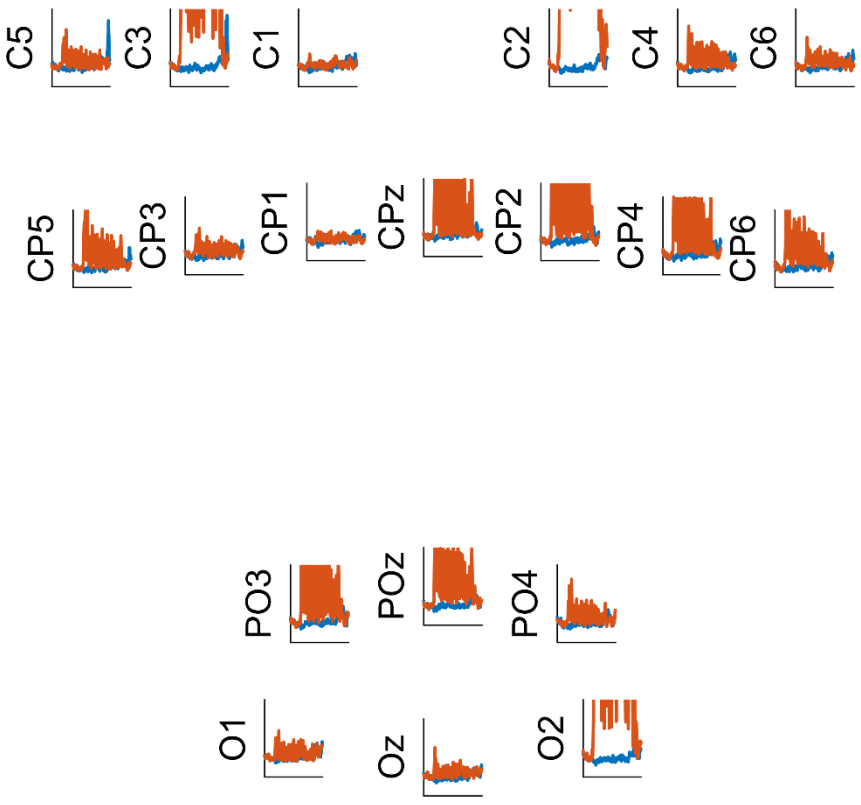

Figure 13. Montage plot of the eEEG results from 20 conventional electrodes from the movement experiment. The movement artefact was observed in the majority of the results.

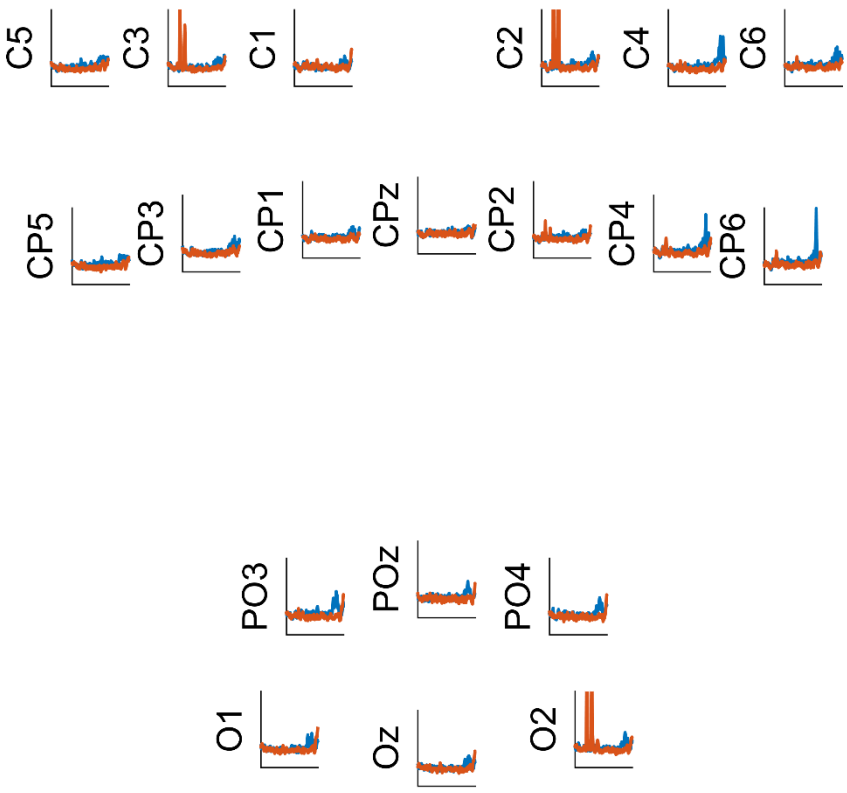

Figure 14. Montage plot of the eEEG results from 20 conventional electrodes from the imagine experiment.

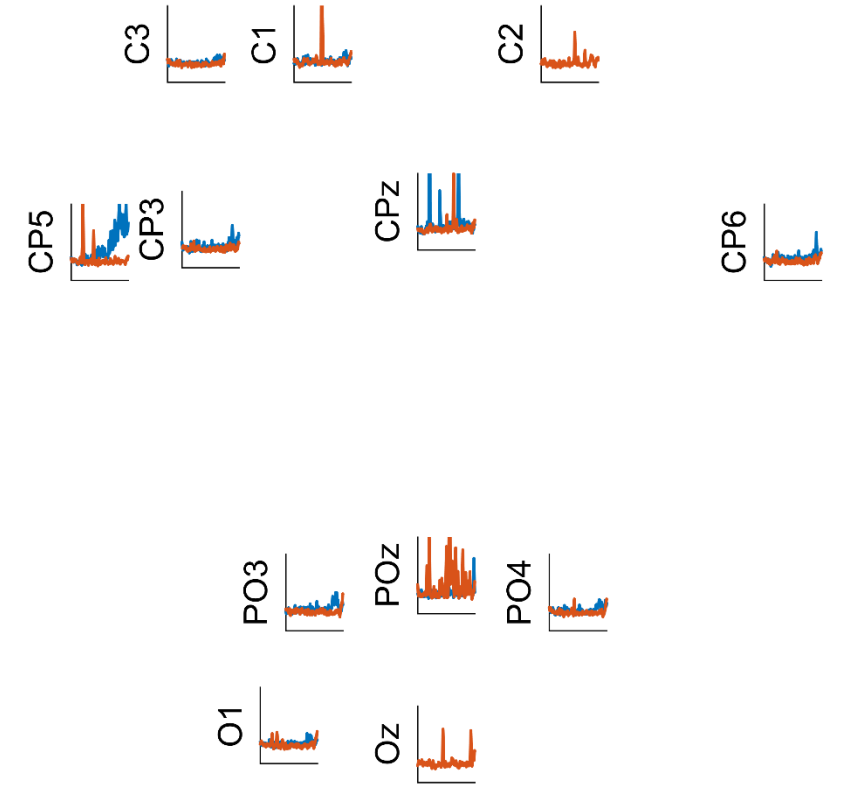

Figure 15. Montage plot of the tEEG results from 20 tCRE electrodes from the imagine experiment. Some channels were considered as bad and deleted.

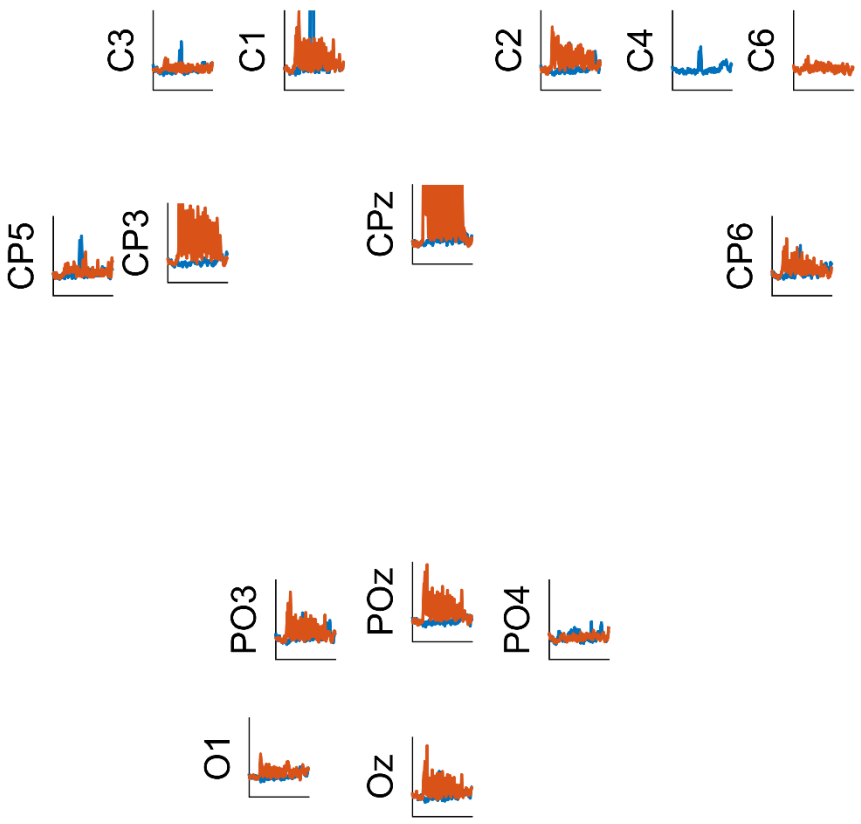

Figure 16. Montage plot of the tEEG results from 20 tCRE electrodes from the movement experiment. Some channels were considered as bad and deleted.

Comparing between Figure 13 and Figure 16, tCRE electrode shows an advantage in reducing movement artefact and a disadvantage in losing channels.

Based on Figure 13, Figure 14, Figure 15, and Figure 16, C3 channels was chosen to be explored as it shows the most information, such as movement artefacts, ERD/ERS, compared to other channels and it is located in the important motor cortex.

Addtionally, in other two region, the sensorimotor cortex and the primary visual cortex, one outstanding performance channel was chose and their results was shown:

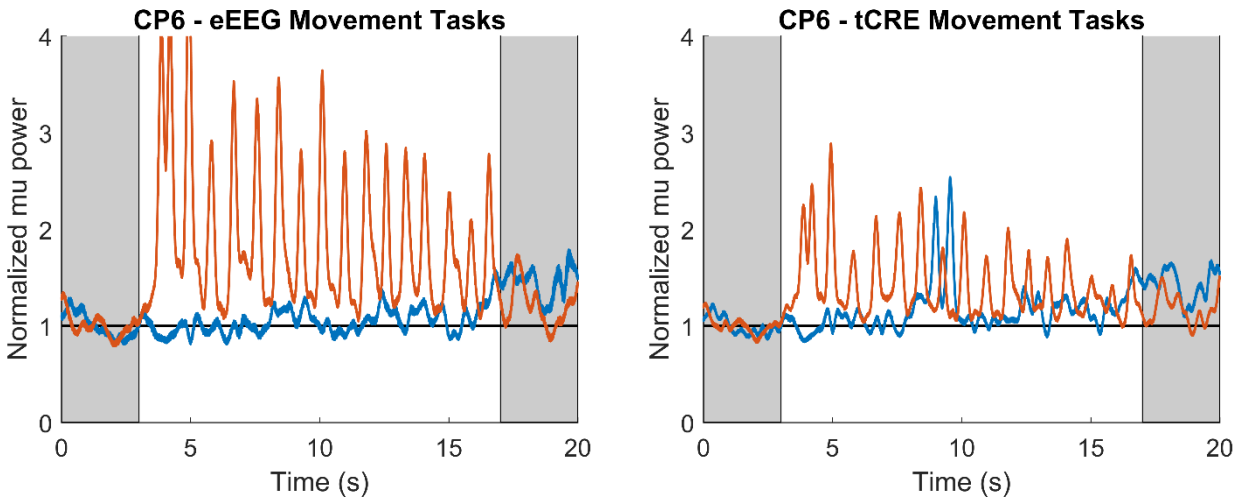

Figure 17. Results of movement tasks were achieved from the emulated electrode (left figure) and the tCRE electrode (right figure) in channel CP6, in the sensorimotor cortex, with averaging among six participants. Both lines showed moderate downward trends in the responding phase, also known as ERD, and followed up with an increment in the second resting phase, also known as ERS. The blue line indicates data acquired from the "Hand tapping task", the red line indicates data acquired from the "Foot tapping task" and the black horizontal line at 1 in Y-axes indicates the baseline for the response. Two grey regions are the resting phase while the white middle region is the responding phase starting from the 3rd second and ending at the 17th second.

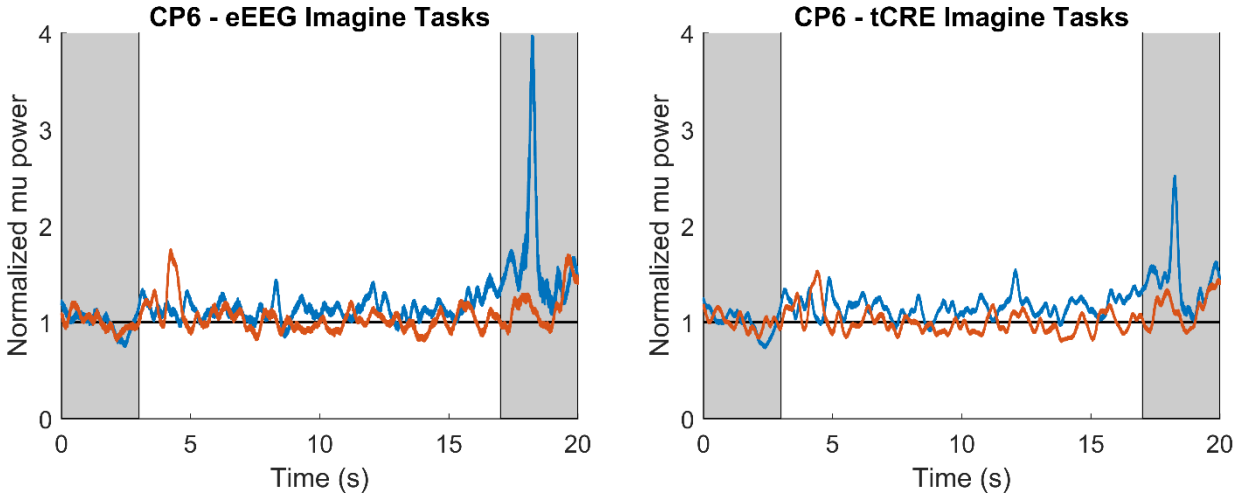

Figure 18. Results of imagine tasks were achieved from the emulated electrode (left figure) and the tCRE electrode (right figure) in channel CP6, in the sensorimotor cortex ,with averaging among six participants. Both lines showed moderate downward trends in the responding phase, also known as ERD, and followed up with an increment in the second resting phase, also known as ERS. The blue line indicates data acquired from the "Hand tapping task", the red line indicates data acquired from the "Foot tapping task" and the black horizontal line at 1 in Y-axes indicates the baseline for the response. Two grey regions are the resting phase while the white middle region is the responding phase starting from the 3rd second and ending at the 17th second.

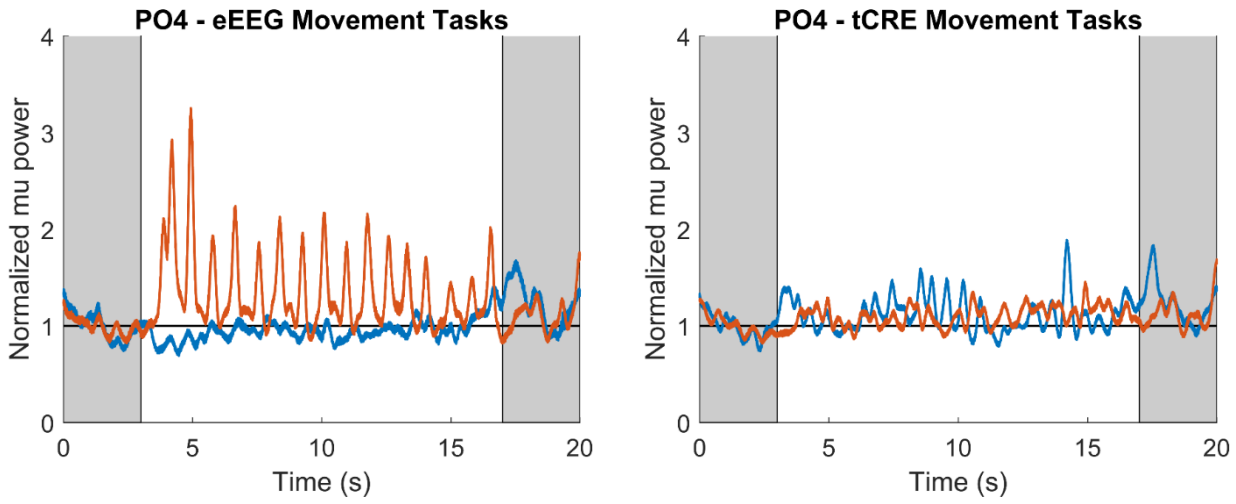

Figure 19. Results of movement tasks were achieved from the emulated electrode (left figure) and the tCRE electrode (right figure) in channel PO4, in the primary visual cortex, with averaging among six participants. Both lines showed moderate downward trends in the responding phase, also known as ERD, and followed up with an increment in the second resting phase, also known as ERS. The blue line indicates data acquired from the "Hand tapping task", the red line indicates data acquired from the "Foot tapping task" and the black horizontal line at 1 in Y-axes indicates the baseline for the response. Two grey regions are the resting phase while the white middle region is the responding phase starting from the 3rd second and ending at the 17th second.

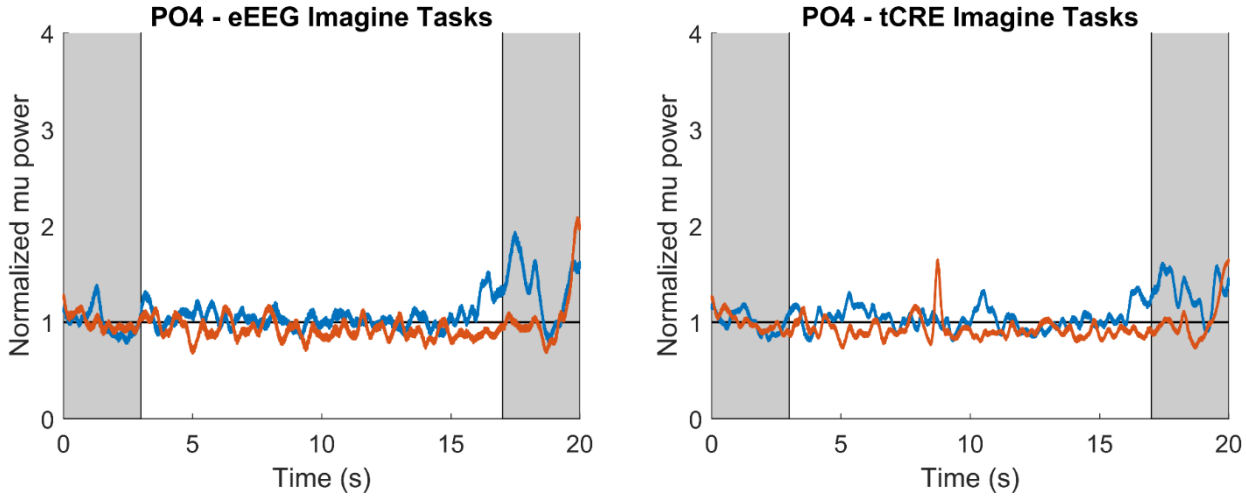

Figure 20. Results of imagine tasks were achieved from the emulated electrode (left figure) and the tCRE electrode (right figure) in channel PO4, in the primary visual cortex, with averaging among six participants. Both lines showed moderate downward trends in the responding phase, also known as ERD, and followed up with an increment in the second resting phase, also known as ERS. The blue line indicates data acquired from the "Hand tapping task", the red line indicates data acquired from the "Foot tapping task" and the black horizontal line at 1 in Y-axes indicates the baseline for the response. Two grey regions are the resting phase while the white middle region is the responding phase starting from the 3rd second and ending at the 17th second.

Appendix C: MATLAB code

Loading up raw EEG, calculating ERD/ERS and ploting results

```
%% Definitions
% what to analyse
participants = { 'P1', 'P2', 'P3', 'P4', 'P5', 'P6'};
tasks = { 'HandTappingAll', 'ImaginedHandTappingAll',
'FootTappingAll', 'ImaginedFootTappingAll' };

% about the recording
reference_chan = 'FCz';
bad_chans = { 'Cz'};% First electrode has significant high
impedance
tCRE_chans = @( x) strcmp( 'tCRE', { x.chan.type};
EEG_chans = @( x) strcmp( 'EEG', { x.chan.type});
chan_type = @( x, y) strcmp( y, { x.chan.type});

% about the analyses
ERD_frequencies = [ 8 12];

% derived
Nparticipants = numel( participants);
Ntasks = numel( tasks);
temp = eeg3.eeg.alloc( 1);
eeg_fieldnames = fieldnames( temp);


%% Load the data
eeglab;

% prepare space for the ERDS time series
tCRE_ERDS = eeg3.eeg.alloc( Nparticipants, Ntasks);
eEEG_ERDS = eeg3.eeg.alloc( Nparticipants, Ntasks);

% loop over participants and tasks
for parti = 1:Nparticipants
    fprintf( '\nLoading data for ...');
    fprintf( '\nParticipant %s, ...', participants{ parti});
    for taski = 1:Ntasks
        fprintf( 'Task %s, ...\n', tasks{ taski});

        % load data and take it out of the cell
        a = load_SMRs( participants{ parti}, tasks{ taski});
        a = a{ 1};
        a = eeglocal.util.addlocation( a);

        % clean the data
```

```
        % delete reference channel
        a = a.discardchans( reference_chan).discardchans(
bad_chans).discardchans( bad_chans);

        % split into tCRE and eEEG :-(
        tCRE = a.selectchan( tCRE_chans( a));
        eEEG = a.selectchan( EEG_chans( a));

        % calculate spectra
        % a_spec( parti, taski, :) = reshape( a.pwelch, [1 1
Ntrials]);

        % Removing artifact for selected channel
        tCRE = tCRE.demeantime; % suppress DC baseline
        tCRE_cleaned = clean_EEG( tCRE);

        eEEG = eEEG.demeantime; % suppress DC baseline
        eEEG_cleaned = clean_EEG( eEEG);


        % Run PCA and reconstruct data
        [coeff, score] = pca( tCRE_cleaned.data);
        tCRE_cleaned.data = score * coeff';
        [coeff, score] = pca( eEEG_cleaned.data);
        eEEG_cleaned.data = score * coeff';

        % Run the continous wavelet transform in the range of
ERD_frequencies
        tCRE_sgram = tCRE_cleaned.cwt( 'frange',
ERD_frequencies).meanfreq;
        eEEG_sgram = eEEG_cleaned.cwt( 'frange',
ERD_frequencies).meanfreq;

        % extract epochs and average
        tCRE_mean = tCRE_sgram.extractepochs( { '25', '28',
'45', '48'}, -0.5, 20.5).relbaseline( 0, 3).mean;
        eEEG_mean = eEEG_sgram.extractepochs( { '25', '28',
'45', '48'}, -0.5, 20.5).relbaseline( 0, 3).mean;

        % cast the ERDS waveform data back into an eeg3.eeg
object
        for fieldi = 1:numel( eeg_fieldnames)
            tCRE_ERDS( parti, taski).( eeg_fieldnames{ fieldi})
= ...
                tCRE_mean.( eeg_fieldnames{ fieldi});
            eEEG_ERDS( parti, taski).( eeg_fieldnames{ fieldi})
= ...
                eEEG_mean.( eeg_fieldnames{ fieldi});
```

```
        end
    end
end

% save the ERDS time series
save ERDS_Cleaned.mat tCRE_ERDS eEEG_ERDS participants tasks
ERD_frequencies tCRE_cleaned tCRE


%% make pictures

% 2021-10-21, 10 channels seem to be common across all
conditions:
% C1, C3, CP3, CP5, CP6, CPz, O1, PO3, PO4, POz
% definitions
display_channel = 'PO4';
xlims = [ 0 20];
ylims = [ 0 4];
line_width = 1.2;
patch_x = [ 0 3 3 0 0; 20 17 17 20 20];
patch_y = [ 0 0 10 10 0];
patch_colour = [ 1 1 1] * 0.8;

% average across people - mean doesn't behave itself here :-(
tCRE_ERDS_mean = tCRE_ERDS( 1, :);
eEEG_ERDS_mean = eEEG_ERDS( 1, :);
for taski = 1:Ntasks
    tCRE_ERDS_mean( taski) = tCRE_ERDS( :, taski).mean;
    eEEG_ERDS_mean( taski) = eEEG_ERDS( :, taski).mean;
end

% average over participants and reshape into useful form for
plotting
plot_data = [ reshape( tCRE_ERDS_mean, [ 2 2]); ...
    reshape( eEEG_ERDS_mean, [ 2 2])];
titles = { 'tCRE Movement Tasks', 'tCRE Imagine Tasks', ...
    'eEEG Movement Tasks', 'eEEG Imagine Tasks'};
Nfigures = size( plot_data, 1);

% loop over the figures we want to make
for figi = 1:Nfigures
    figure( figi), clf, hold on;
    plot_data( figi, :).selectchan( display_channel).plot( ...
        'XLim', xlims, 'YLim', ylims, 'LineWidth', line_width);
%     plot_data( figi, :).plotmontage( ...
%         'XLim', xlims, 'YLim', ylims, 'LineWidth',
line_width);
```

```
    patch( patch_x( 1, :), patch_y, -1 * [ 1 1 1 1 1],
patch_colour);
    patch( patch_x( 2, :), patch_y, -1 * [ 1 1 1 1 1],
patch_colour);
    plot3( xlims, [ 1 1], -0.5 * [ 1 1], 'k-', 'LineWidth',
line_width);
    ylabel( 'Normalized mu power');
    title( sprintf( '%s - %s', display_channel, titles{
figi}));
    %print figure as *.png
    pretty_print('filename', sprintf( '%s - %s - 80%
correllation', display_channel, titles{ figi}), 'target',
'thesis')
end


%% do the stats

% definitions
responding_times = [ 3.5 17];
resting_times = [ 17 20];
test_channels = {'C6'};
%test_channels = { 'C1', 'C3', 'CP3', 'CP5', 'CP6', 'CPz',
'O1', 'PO3', 'PO4', 'POz'};

% calculate responding and resting mu power
tCRE_responding = tCRE_ERDS.selecttime( ...
    responding_times( 1), responding_times( 2)).meantime;
eEEG_responding = eEEG_ERDS.selecttime( ...
    responding_times( 1), responding_times( 2)).meantime;
tCRE_resting = tCRE_ERDS.selecttime( ...
    resting_times( 1), resting_times( 2)).meantime;
eEEG_resting = eEEG_ERDS.selecttime( ...
    resting_times( 1), resting_times( 2)).meantime;

% test some hypotheses
for chani = 1:numel( test_channels)
    fprintf( '\nTesting at channel %s\n', test_channels{
chani});
    for taski = 1:Ntasks
        [ h, p] = ttest( [ tCRE_responding( :,
taski).selectchan( test_channels{ chani}).data] - 1);
        if h == 0
            fprintf( 'No evidence of ERD for %s in %s with
tCRE, p = %0.3f\n', ...
                tasks{ taski}, test_channels{ chani}, p);
        else
```

```
            fprintf( 'Yes! ERD for %s in %s with tCRE, p =
%0.3f\n', ...
                tasks{ taski}, test_channels{ chani}, p);
        end
        [ h, p] = ttest( [ tCRE_resting( :, taski).selectchan(
test_channels{ chani}).data] - 1);
        if h == 0
            fprintf( 'No evidence of ERS for %s in %s with
tCRE, p = %0.3f\n', ...
                tasks{ taski}, test_channels{ chani}, p);
        else
            fprintf( 'Yes! ERS for %s in %s with tCRE, p =
%0.3f\n', ...
                tasks{ taski}, test_channels{ chani}, p);
        end
        [ h, p] = ttest( [ eEEG_responding( :,
taski).selectchan( test_channels{ chani}).data] - 1);
        if h == 0
            fprintf( 'No evidence of ERD for %s in %s with
eEEG, p = %0.3f\n', ...
                tasks{ taski}, test_channels{ chani}, p);
        else
            fprintf( 'Yes! ERD for %s in %s with eEEG, p =
%0.3f\n', ...
                tasks{ taski}, test_channels{ chani}, p);
        end
        [ h, p] = ttest( [ eEEG_resting( :, taski).selectchan(
test_channels{ chani}).data] - 1);
        if h == 0
            fprintf( 'No evidence of ERS for %s in %s with
eEEG, p = %0.3f\n', ...
                tasks{ taski}, test_channels{ chani}, p);
        else
            fprintf( 'Yes! ERS for %s in %s with eEEG, p =
%0.3f\n', ...
                tasks{ taski}, test_channels{ chani}, p);
        end
    end
end
```

Clean EEG function

```
function a=clean_EEG (a)
for ai=1:numel(a)
    clear EEG
    fprintf('Clean trial number %d\n',ai);
```

```
    EEG=eeg2eeglab( a(ai), 'rejectartifact', true);
    a(ai)= eeg3.eeg;
    EEG_cleaned=
clean_artifacts(EEG,'ChannelCriterion',0.80,'BurstCriterion','o
ff','WindowCriterion','off');
    a(ai) = eeg3.util.eeglab2eeg( EEG_cleaned);
end
end
```