Final Project
Neuroscience of Learning, Memory, Cognition
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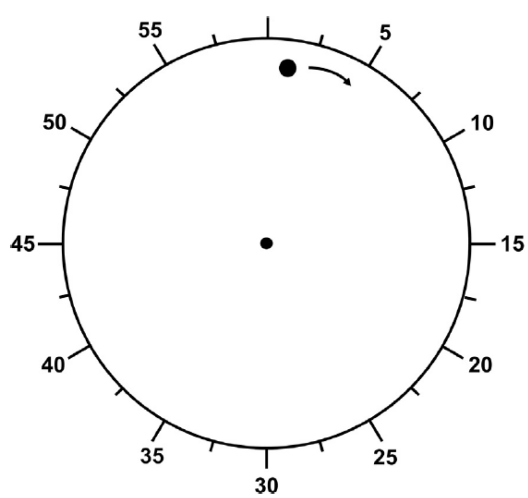
Question 1

Explaining the experiment in details

The experiment is based on the original study by Libet et al. (1983), which aimed to measure the timing of conscious intention to act and its relation to brain activity and motor action. Dominik et al. (2018) replicated Libet's experiment with a similar methodology, but with some modifications and improvements.

The procedure of the test and trials of this experiment is mainly described in the following :

- The participants (4 male, 4 female) were seated in a comfortable medical armchair in a sound-attenuated and electrically shielded room. They wore a cap for EEG recording and two electrodes on their forearm for EMG recording. They also wore soft earplugs and there is a mouse for reporting their subjective events by clicking.
- The participants were instructed to watch a rotating spot on a circular screen that resembled a clock face. Generally, the participants were asked to either make a movement (click the left mouse button) or wait for a skin stimulus to be delivered while watching the center of the running clock.
- After that the participants will report the location of the moving dot when they registered a specific introspective impression.



Modes of recall (A or O)

As we mentioned before, the participants had to report the location on the moving dot. This report could be made by two modes of recall :

1. **Absolute mode (A) :**
   This mode is a straight-forward approach. Participants simply clicked on a specific spot on the clock face where the dot was when their impression first occurred.
2. **Order mode (O) :**
   After the time that the participant clicked or a skin stimulus delivered, the dot continue moving for a random time in interval of 500 to 800 ms. After that the dot will jump to a specific stop time(one of the 41 possible values from the range of 400 ms before and 200 after the event).
   Participants should compare the timing of the subjective impression with the current dot's location. They should state whether their impression comes before the stop time, after that or exactly at the stop time.

Types of the experimental tasks

The experiment consisted of five series of trials: **M, W, S, P** and **Pv**.

- **M Series :**
  Participants should click the left mouse button whenever they felt like it, without any pre-planning or anticipation. Then they were asked to report the time of subjective recall of the beginning of the movement (M).

- **W Series :**
  This type is almost similar to the M series. In the W series, participants reported when they realized the first urge to move (W).

- **S Series :**
  The difference of this type with the previous ones is that the event is skin stimulus instead of mouse click. The participants should wait for the stimulus driven by a tactile stimulator at random time. They should report the time in which they registered the stimulus.

- **P Series :**
  There is also a fixed green dot on the clock screen in this task which appeared on a random position. Participants should click the mouse when the moving dot reached the green dot. There will be no response prompt in this type.

- **Pv Series :**
  Participants were instructed to prepare to click the mouse button exactly at the time marked by the target point, but then stop (veto) the movement just before it begun.

Question 2

Libet's purpose in designing task S was to have a "correction" for how accurate participants' time perception was. He wanted to test the validity and reliability of his method of measuring subjective event timing.
He wanted to compare the accuracy and precision of the participants' reports of W and M times with their reports of S times.

Question 3

The authors made some modification in the design of the experiment in comparison the Libet's original one. They have stated that some modifications were necessary, either for technical or for methodological reasons.

Some of the most important differences between their replication and Libet's original experiment are:

- Libet worked with 6 participants while in this experiment there are 8 participants. The number of 8 participants has a rational reason. 8 is divisible by 4 which allows a complete rotation of three experimental conditions, which could not be satisfyingly rotated if we examined 6 participants only.

- In Libet's original experiment, participants had to performed simple finger or wrist movements. In this experiment mouse click is used for several reasons. This choice might bring some advantages. Using mouse click they were able to compare the time of the mouse click to an EMG onset. It is important the the participants determine the timing of their movement easily to have more accurate timing reports. Mouse click is far more abrupt and better bounded movement in comparison to wrist or finger movement.

- Unlike Libet's original experiment, the authors decided not to provide any feedback in S series tasks and they remove the 25 initial S series trials from all sessions.
  Libet considered 25 S series trials at the beginning of each session to give accurate introspective report. He

provided feedback to participants on how close their response were to the time of actual stimuli. Studies and experiments after Libet's showed that this process might lead to variable results across the sessions. Also since reports provided after an auditory feedback training would presumably differ from those provided after a tactile feedback training, there seems to be no reason to use the training based on the skin stimulation specifically.

- Libet measured EOG for the first few sessions to check and monitor unwanted eye movement. It seemed that the participant could satisfyingly concentrate on the center of clock. The EOG data is unnecessary and instead it makes the participant discomfort so in this experiment EOG is not recorded and is completely omitted.
- The authors used a different stimulus to trigger the movement in Task S. They used a tactile stimulus, while Libet used an electrical stimulus on the hand or wrist[1]. They argue that this method is more natural and less painful than Libet's method.

Question 4

The grand average calculated for EEG signals is a way of combining the EEG data from multiple trials or participants to obtain a representative EEG signal for a given condition or task. The grand average is usually computed by aligning the EEG signals in time and then averaging them point by point across trials or participants.
In this experiment, they plotted the mean courses of activation based on all 17,669 valid trials in respective series regardless of the session, but with respect to the electrode.

Question 5

We will use python to regenerate the Fig 6 plot of the article. This figure consists of three curves. each one belongs to one of the M series, W series and S series tasks. Each curve represents the average value of response for each of the participant. the 95% intervals can be seen too.

We first insert and upload our data set to a pandas data frame and separate data of each type of tasks:

```
df_dict = pd.read_excel("Introspective data file.xlsx", sheet_name=None)

M_df = df_dict['M(A)']
W_df = df_dict['W(A)']
S_df = df_dict['S(A)']
```

Next we have to calculate the average and standard deviation of our data. So we extract the resp<>EMG columns of our data frame and replace values denoted by 'no EMG' with zero. These are the trials we should not consider in our calculation but as the question said we just replace them with zero just for ease. we note that this will make our results less accurate.

```
M_resp_timing = M_df.filter(regex='resp<>EMG').replace({"no EMG" : 0}).values
W_resp_timing = W_df.filter(regex='resp<>EMG').replace({"no EMG" : 0}).values
S_resp_timing = S_df.filter(regex='resp<>stimulus').replace({"no EMG" : 0}).values
```

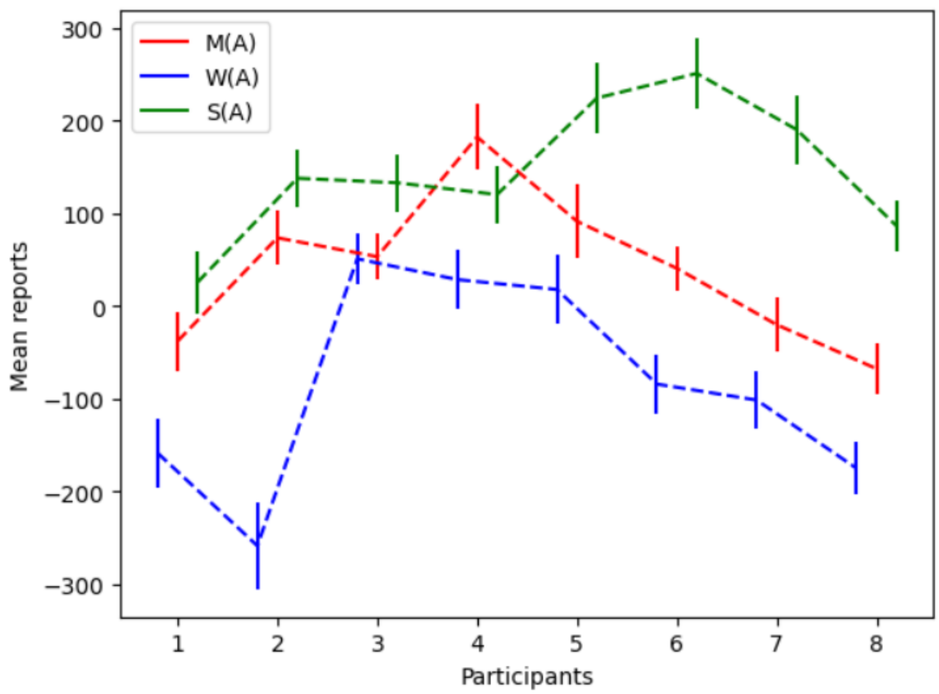
For M series tasks, there two session for each participant except for participant 4. Since participant 4 has one session recording less than others, there will be a 'nan' in our matrix which we have replaced it with the corresponding value of the only one session recording available. We will compute the average and standard deviation for each session and finally we will report the average of results. There are 3 session recording for all participants in W series and 2 session recording for S series.

```
M_avg = np.reshape(np.mean(M_resp_timing, axis=1), (-1, 2))
W_avg = np.reshape(np.mean(W_resp_timing, axis=1), (-1, 3))
S_avg = np.reshape(np.mean(S_resp_timing, axis=1), (-1, 2))
```

```python

    M_std = np.reshape(np.std(M_resp_timing, axis=1), (-1, 2))
    W_std = np.reshape(np.std(W_resp_timing, axis=1), (-1, 3))
    S_std = np.reshape(np.std(S_resp_timing, axis=1), (-1, 2))

    M_avg = np.mean(np.nan_to_num(M_avg, nan=182), axis=1)
    W_avg = np.mean(W_avg, axis=1)
    S_avg = np.mean(S_avg, axis=1)

    M_std = np.sqrt(np.mean(np.nan_to_num(M_std, nan=138.152), axis=1))
    W_std = np.sqrt(np.mean(W_std, axis=1))
    S_std = np.sqrt(np.mean(S_std, axis=1))
```

Finally we visualize the data using matplotlib errorplot function :

```python
    plt.errorbar(np.linspace(1,8,8), M_avg, yerr=3*M_std, linestyle='--', c='red')
    plt.errorbar(np.linspace(1,8,8)-0.2, W_avg, yerr=3*W_std, linestyle='--', c='blue')
    plt.errorbar(np.linspace(1,8,8)+0.2, S_avg, yerr=3*S_std, linestyle='--', c='green')
```



Based on the W curve from above figure, it can be seen that the value of three points are positive. this means that three participants reported the W reports after the EMG onset on average. Also its interesting that W reports and M reports of participant 3 have quit the same average values while there is a notable difference between these values for other participants especially for participant 2.

Question 6

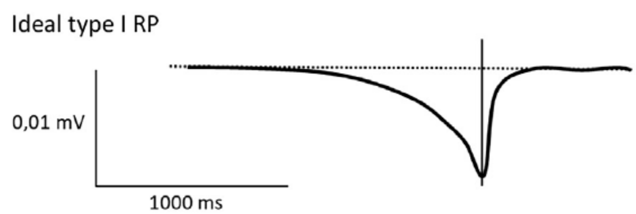
RP stands for **readiness potential**, which is a brain signal that precedes voluntary movement. It is a slow buildup of EEG signals. It is associated with neural activity involved in movement preparation.
Libet defined RP as the negative potential shift that occurs before a self-initiated movement. Libet interpreted the

RP as a reflection of unconscious neuronal processes that initiate and prepare for voluntary action.

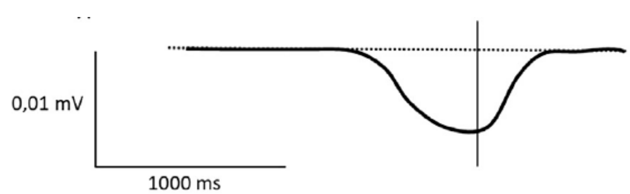
The start time of RP on the EEG charts can be recognized by looking for a gradual decrease in voltage that begins about 1 second before the movement onset. The RP reaches its peak at the movement onset and then returns to baseline. The RP is more prominent at central electrode sites located above mesial motor cortical areas and peaks contralateral to the moving limb.

There are three type of RPs:

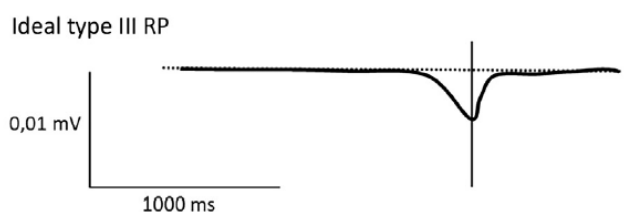
1. **Type I RP :**
   In type I RP a gradually or steadily rising, ramp-like form begins distinctly prior to -700 ms.



2. **Type II RP :**
   In type II RPs, the main rise of negativity starts in the range of about−400 to−700 ms and is often dome-shaped rather than ramp-like.



3. **Type III RP :**
   the main rise of negativity does not appear until about−250 to−200 ms.



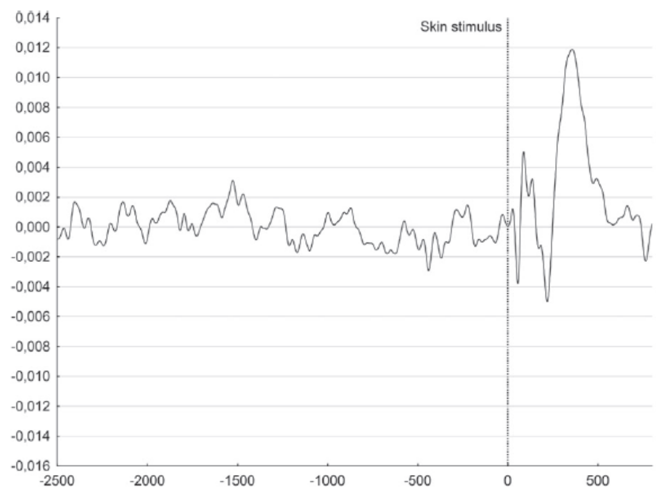
The RP is expected to precede the movement onset in the M, W, P and Pv series and their presence and onsets were assessed

Question 7

ERP stands for event-related potential, which is a brain signal that reflects the neural response to a specific event or stimulus. ERP can be measured by recording the electrical activity of the brain using EEG or MEG. ERP can be used to study various cognitive processes, such as perception, attention, memory, language, emotion, and decision-making. ERP can also reveal the temporal dynamics and neural mechanisms of these processes by analyzing the amplitude and latency of different components or peaks in the ERP waveform . Two types of ERP are the readiness-potential (RP) and the P300 wave.

P300 reflects the neural response to a rare or unexpected stimulus. P300 is characterized by a positive deflection in the EEG signal that occurs about 300 milliseconds after the stimulus onset. P300 can be used to study various cognitive functions, such as perception, language, emotion, and decision-making. The P300 is a cognitive ERP expected to follow the stimulus presentation in the S series. The P300 wave only occurs if the subject is actively engaged in the task of detecting the targets.

P300 in S series, C_3, participant 3, 41 valid trials



Question 8

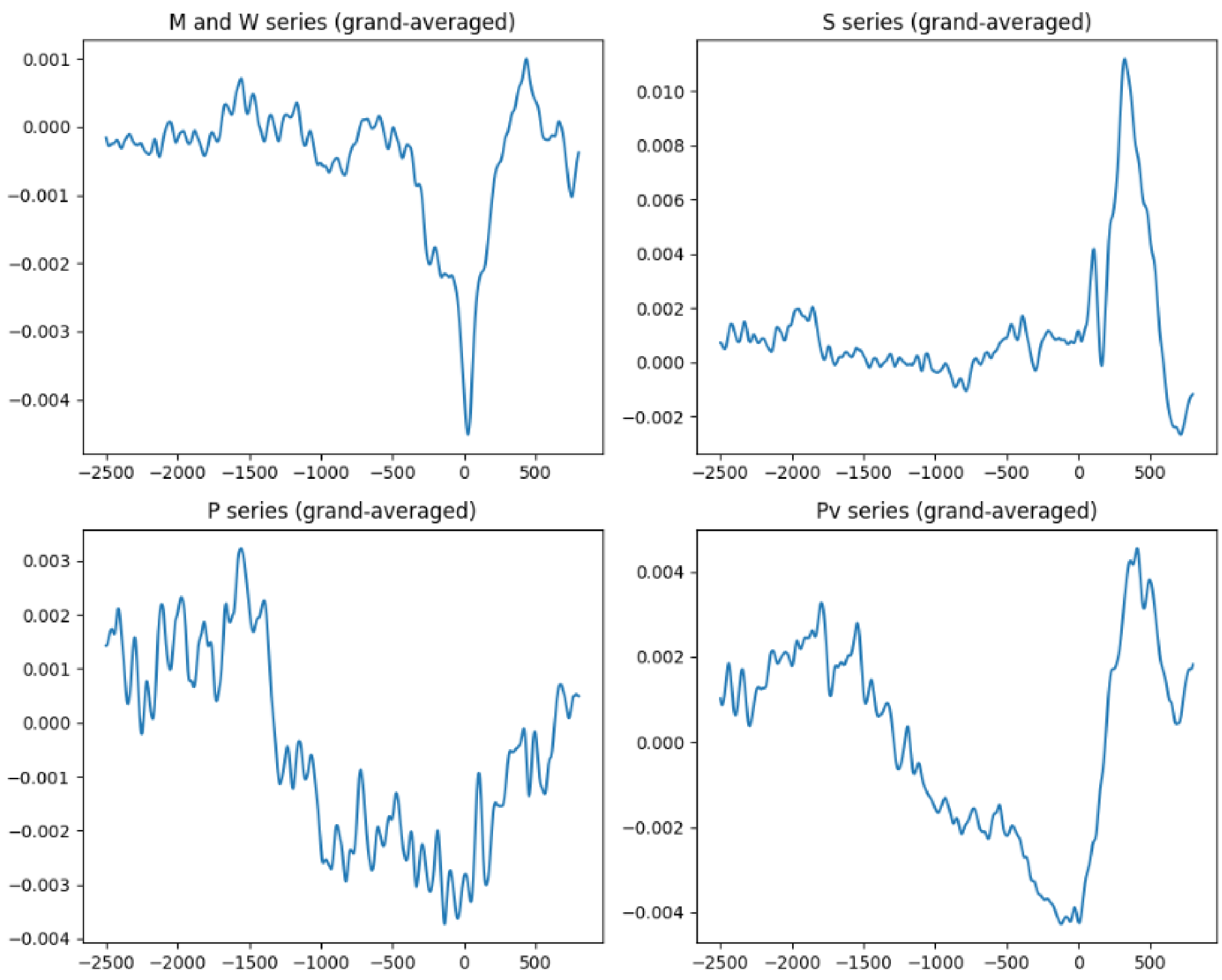
First we try to create grand averaged EEG data figures and curves like figure 10 in the article.

We load the data from "Grand Average" sheet of the "EEG plot file.xlsx" file into a pandas data frame. Then we should choose and extract data corresponding to Cz channel for each type of tasks :

```
df = pd.read_excel("EEG plots file.xlsx", sheet_name='Grand Average')

MW_data = df.loc[(df['electrode'] == 'Cz') & (df['series'] == 'W/M')].values.T
S_data = df.loc[(df['electrode'] == 'Cz') & (df['series'] == 'S')].values.T
P_data = df.loc[(df['electrode'] == 'Cz') & (df['series'] == 'P')].values.T
Pv_data = df.loc[(df['electrode'] == 'Cz') & (df['series'] == 'Pv')].values.T

MW_data = np.reshape(MW_data[3:], -1)
S_data = np.reshape(S_data[3:], -1)
P_data = np.reshape(P_data[3:], -1)
Pv_data = np.reshape(Pv_data[3:], -1)
```

Finally we visualize the grand averaged signal for each type of tasks in different subplots.

```
    fig, ax = plt.subplots(nrows=2, ncols=2, figsize=(10,8))
    ax[0, 0].plot(t, MW_data)
    ax[0, 1].plot(t, S_data)
    ax[1, 0].plot(t, P_data)
    ax[1, 1].plot(t, Pv_data)
    ax[0, 0].set_title('M and W series (grand-averaged)')
    ax[0, 1].set_title('S series (grand-averaged)')
    ax[1, 0].set_title('P series (grand-averaged)')
    ax[1, 1].set_title('Pv series (grand-averaged)')
```



It can be seen that the results are the same as the figures shown in the article itself.

Now in order to plot and visualize the ERP signal of each participant for different tasks, we will create 5 figures corresponding to each type of task. Each figure will contain 8 curves for each participant.

We first load our dataset from ”Individual EEG” sheet of the given excel file. Our dataframe contains lots of data for different participant, task, channels,... . For ease of use and more professional coding, we define a data structure. For each participant we create a python dictionary which it's keys are the task types and it's values are Cz channel EEG signal. In order to do so we have developed a function called "create_personal_data()" which receives the number of the participant as input argument and returns the dictionary. In this function we will choose data corresponding to that participant and the Cz channel for different type of tasks. The code of this function is as follows :

```
def create_personal_data(id):

M_data = df.loc[(df['electrode'] == 'cz') & (df['series'] == 'M') & (df['participant'] ==
    id)].values.T
W_data = df.loc[(df['electrode'] == 'cz') & (df['series'] == 'W') & (df['participant'] ==
    id)].values.T
S_data = df.loc[(df['electrode'] == 'cz') & (df['series'] == 'S') & (df['participant'] ==
    id)].values.T
P_data = df.loc[(df['electrode'] == 'cz') & (df['series'] == 'P') & (df['participant'] ==
    id)].values.T
Pv_data = df.loc[(df['electrode'] == 'cz') & (df['series'] == 'Pv') & (df['participant'] ==
    id)].values.T

M_data = M_data[11:]
W_data = W_data[11:]
S_data = S_data[11:]
P_data = P_data[11:]
Pv_data = Pv_data[11:]

dict = {
  "M_data" : M_data,
  "W_data" : W_data,
  "S_data" : S_data,
  "P_data" : P_data,
  "Pv_data" : Pv_data
}

remove_data = []
for data in dict:
  if dict[data].shape[1] == 0:
  remove_data.append(data)
for item in remove_data:
  dict.pop(item)

return dict
```

Data for some Tasks are not available in the given dataset. For example there are no data for the Pv series tasks surprisingly. Also for some participant some type of tasks aren't available too so we have removed any possible empty data from our dictionary.

After creating this dictionary for all participants, we push all these dictionaries in a list called "all_dict".

```
all_dict = [p1_dict, p2_dict, p3_dict, p4_dict,
            p5_dict, p6_dict, p7_dict, p8_dict]
```

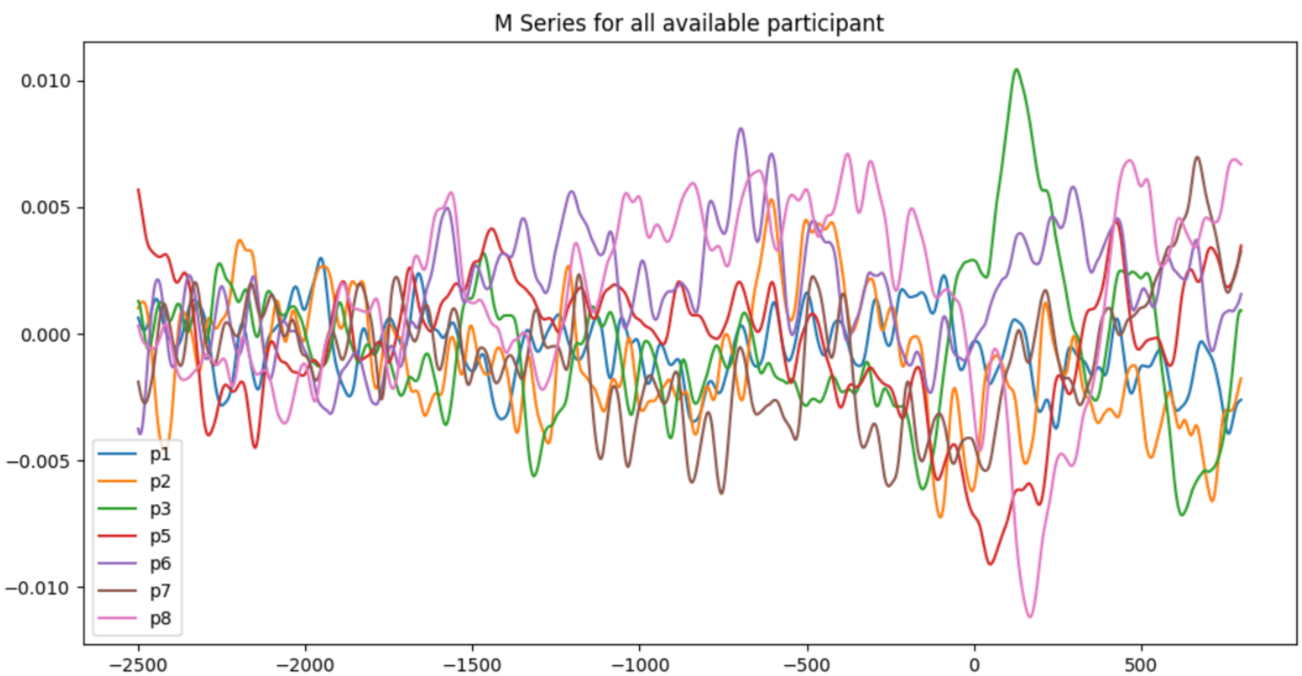
We noticed that for each participant there might be more than one EEG signal with the desired specifications (type of task, channel) so we should be careful when we want to plot theses signals. We have simply decided to choose only one of these signals.

Now its time to visualize our data for each type of tasks. Here we will plot the curves for the M series tasks. First we choose dictionaries of all participants that have this type of task :

```
data = []
labels = []
for i in range(len(all_dict)):
  if 'M_data' in all_dict[i].keys():
    data.append(all_dict[i])
    labels.append('p'+str(i+1))
```

Then we visualize the results.

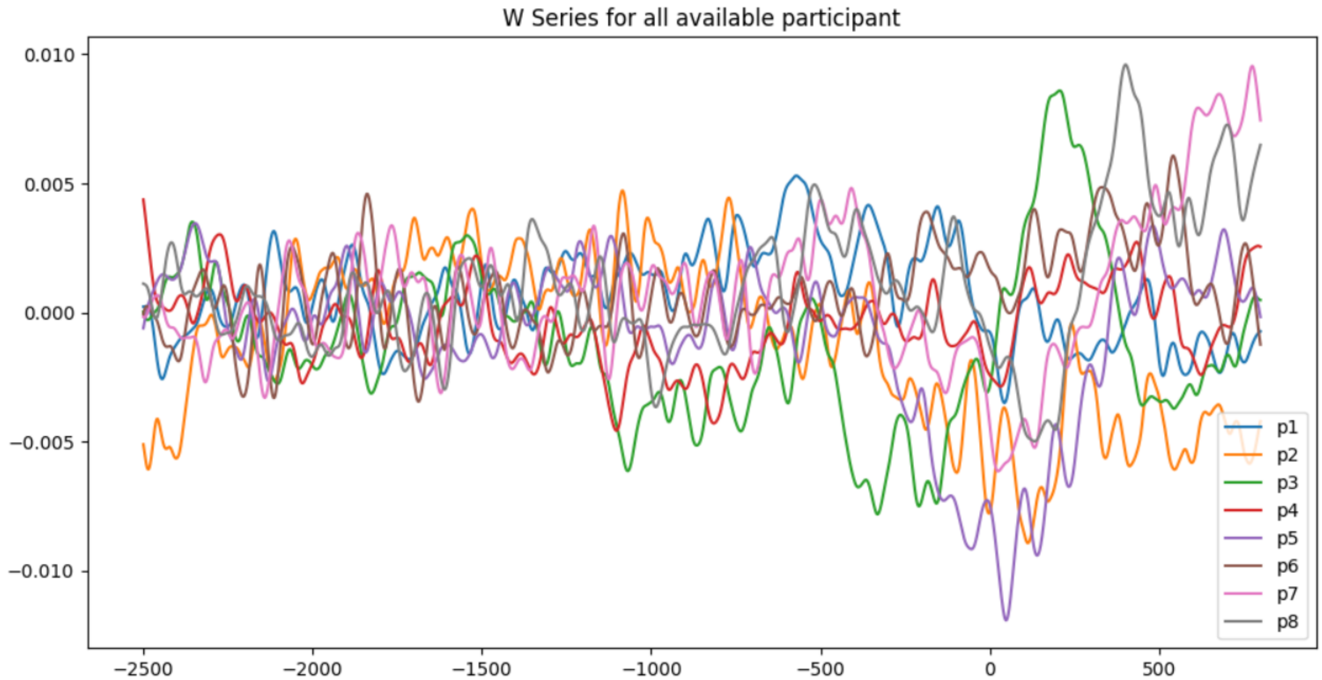
```
plt.figure(figsize=(12,6))
plt.title('M Series for all available participant')
for i in range(len(data)):
  plt.plot(t, data[i]['M_data'][:,0], label=labels[i])
plt.legend()
plt.show()
```



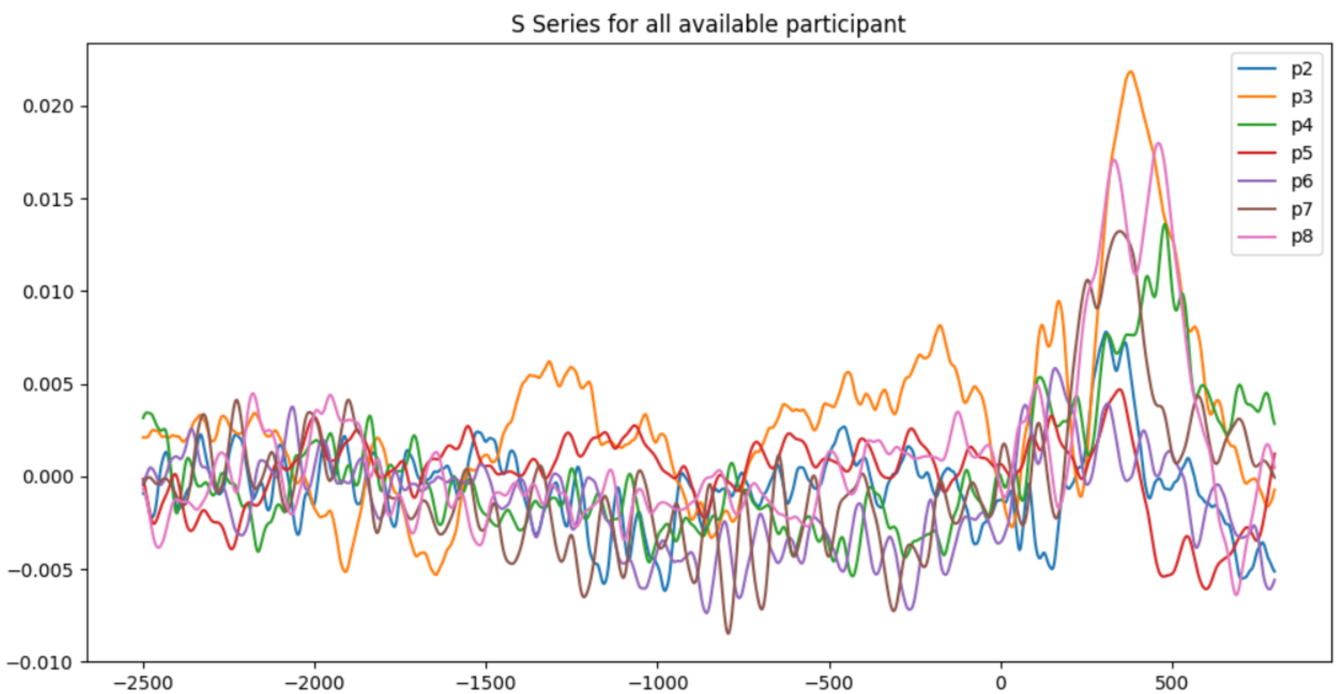
We will try to find the RP by observing the above figure. Based in the typical shape of RPs we can quit state that the RP can be detected for the participants 2, 6 and 8. These RPs are type I.

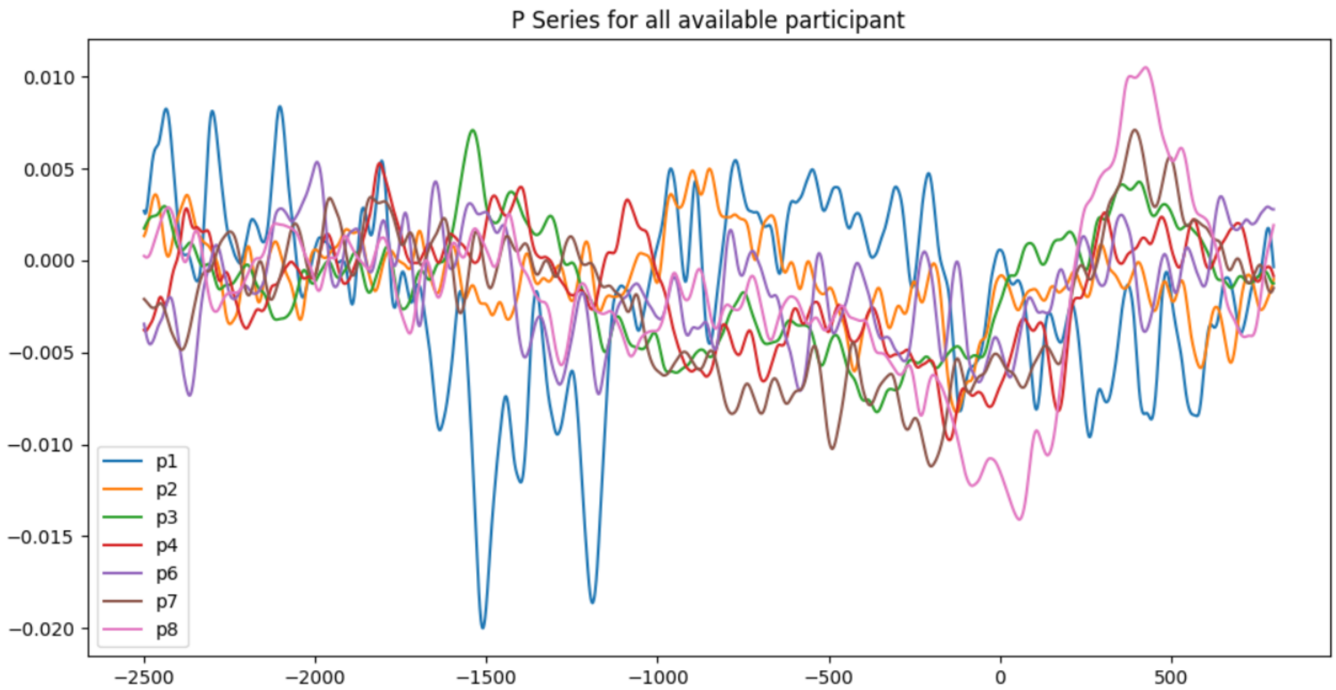
Participant	1	2	3	4	5	6	7	8
RP timing (ms)	no RP	-600	no RP	no data	-550	no RP	no RP	-450

The procedure of generating these plots for other type of tasks are the same so here we see only the results.



Participant	1	2	3	4	5	6	7	8
RP timing (ms)	no RP	-480	no RP	no RP	-500	no RP	-450	-200





Question 9

Libet's clear message from his experiments was that **conscious free will** is not involved in the initiation of voluntary actions, but only in the **possibility of vetoing them**. He argued that our brains decide to act before we become aware of our intention to act, and that this challenges the traditional view of free will as a conscious and causal agent.

In the M and W series, Libet asked the participants to report the time of their conscious intention or awareness of wanting to move by using a rotating spot method. He compared this time with the onset time of the RP. The RP onsets generally precede not only the movement itself, but also the conscious awareness of wanting to move. He found that the RP began about **550 ms** before the movement onset, while the conscious intention occurred only about **200 ms** before the movement onset. He concluded that the RP reflects an unconscious decision to act that precedes and determines the conscious intention.

In another series of experiments including veto possibility, he found that the RP still occurred before the planned movement time, but it was reduced or abolished when the participants vetoed their movement. He concluded that the veto is a conscious act of free will that can inhibit the final motor output of an unconscious decision.

Question 10

Thee figures and results show that if an RP was found, it almost universally tends to precede the W report. However, in some series of one participant, the mean W report was remarkably close to RP_MN onset (especially participant 2). It seems suggestive that the RP does not precede the intention to act in all participants.

The import point we have to consider in interpretation of the results is that the variance and changeability of our data are notably large. For example, the average value of M series time reported by Libet was -86 ms while our data shows average of 30 ms. Libet's W report was -204 ms on average while our data shows a value of -90 ms. These gap between the reported values are considerably noticeable.

Based on figure of question 6, except for participant 3, the average value of M reports are higher than the average value of W reports. Based on these figures it can be seen that the recorded data is notably different across participants.

Question 11

In 17 of the 48 sessions, the participants said that they feel any pre-planning before moving the finger. One of the participants said that approximately 8 trials in one W(A) series (absolute mode of recall) were pre-planned. In this case, the detected ERP was type II RP with onset of -700 ms which were earlier than the sample average -212 ms.

Also that participant reported that about 6 trials in the M(A) series (absolute mode of recall) were also pre-planned. The type II RP detected in this case had onset of -310 ms which is substantially earlier than the sample average -85 ms.

Question 12

An earlier study by Gomes (1998, p. 590) after the Libet's original experiment, figured out that this feedback might lead to variable results across sessions. This will certainly change the results leading to large inconsistencies in data obtained in the first few sessions compared to data acquired in the last sessions.
Another study showed that introspective reports differ for tactile, visual and auditive modality. this implies that the reports provided after an auditory feedback training would presumably differ from those provided after a tactile feedback training. Therefor, there seems to be no reason to use the training based on the skin stimulation specifically.

the authors wanted to avoid any influence of feedback on the participants' subjective reports. They argued that feedback could bias the participants' perception of their intention and movement timing, and thus affect the validity of their data. Feedback could create a learning effect, in which the participants could adjust their reports based on the feedback and improve their accuracy over time .

Question 13

As we mentioned in **Question 3**, unlike Libet that used wrist or finger movement, the authors of this article decided to choose mouse click instead. Their choice have several reasons as they stated.
They weren't able to control the computer and their technical setup using EMG signals, so they use mouse click to stop the Libet's clock.

They assumed that using mouse click can bring them some advantages. First using mouse click and comparing the time of the mouse click and the EMG onset, they want to verify a previous study that stated that key press typically occurs 30-50 ms after the EMG onset.

Since mouse click is a more abrupt and better bounded movement in comparison to finger or wrist movement, it will be easier for the participants to determine the timing of their movement. This can lead to more accurate and valid reports and data.

There is also a problem with this type of movement. By clicking a mouse a delayed auditory feedback will be created. This feedback can distort the W reports. In order to remove and eliminate this factor, participants are provided with earplugs so that they can't hear the mouse click. In addition to this, mouse click will provide a slight haptic feedback. Also since the clicking process is a small and fast movement, the probability that the EMG onset doesn't record properly will increase. Using the wrist or finger movement we will face this problem with lower priority because more muscle fibers will be activated in this case.