The Effect of Conscious Intention on the Error Potential in Free Movement

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Abstract

In this pilot study on movement intention it is assessed whether it is possible to detect an intention to move based on EEG data. To this end participants perform a free movement task during which their intention to move is predicted. When a prediction is made the participant is interrupted. The hypothesis is that such an interruption leads to an error potential-like response, of which the amplitude differs as a function of whether the participant reports an intention to move. Such a brain response is indeed visible as a result of this experiment and is consistent across participants. The amplitude of the brain response is greater when participants report not having had an intention to move at the time of the prediction. Based on the limited amount of data collected this difference is not statistically significant, however a larger study should be conducted to draw final conclusions.

1 Introduction

Every day, humans are faced with many decisions. Often, we make choices without being aware that there was a decision to be made in the first place. However, most people, if asked, would probably still state that they made the choice themselves and that they are capable of acting freely and out of their own will [1]. This opens up questions on how our brain prepares for action and what role conscious intent plays in choosing, and preparing for, these actions.

Thanks to recording techniques such as EEG we now have access to data that can give insight into what happens in the brain before a person starts to act. As a result, the topic of consciousness and movement intent has become an active area of research [2,3].

In a study by Libet et al [2] participants were asked to move their hand as soon as they felt a conscious intention to move. Participants were placed in front of a revolving clock and reported the position of the hand at the moment when they felt the intention to act. After each movement they were asked to recall at what time they felt the intention arise. At the same time Libet et al recorded EEG data from the participants' brain to observe the changes in brain activity prior to movement onset.
Libet et al found that the time at which a participant reports being aware of an intention to move is before the onset of the actual movement, but after the brain shows signs of movement preparation (i.e. a readiness potential) [4]. This finding implies that there are processes in the brain that we are not aware of but that are involved in the preparation of an action at a time where the participant is not conscious of the decision themselves and calls into question the role of conscious intent in the decision making process [2]. The experiment has been reproduced and adapted multiple times since [3,5].

Instead of asking participants to recall the onset of their intention to act in retrospect, Matsuhashi et al ask their participants to perform self paced movements, but additionally play a sound at random times during the experiment. When a sound is presented and the participant is consciously preparing for or thinking of a movement, they are instructed to abort the movement and wait for a while before continuing the task. If they are not preparing for or thinking of a movement at that time, they can simply ignore the sound and continue their task. [3]. To determine at what time participants are aware of their intention to act Matsuhashi et al analyse the distribution of the timing of the tones relative to the time of movement onsets. This distribution shows a clear decrease in the number of tones played almost one and a half seconds before the onset of a movement, which suggests that humans are aware of their intention to move much earlier than Libet at al. thought, who estimated the onset of intention to occur around 200ms prior to action performance [2].

A slightly different approach to study motor intent in humans is taken by Verbaarschot et al [6]. In their study participants play a game against 'the computer'. The participants' goal is to press a button in an unpredictable manner. However, if the computer detects an intention to move in the participant based on the participant's action history or ongoing EEG, it moves immediately, causing the participant to loose that round in the game. Each time a prediction occurs, the participant is asked to report whether they felt an intention to move at that point in time.

Verbaarschot et al express that the brain response to a prediction may be related to an error potential. In their results a negative peak followed by a positive peak are visible in the first second after the participant is made aware that a prediction occurred.

In the following this hypothesis is explored further. Through an experiment inspired by Matsuhashi et al [3] it is investigated whether changes in the EEG signal recorded from the participants after interrupting self paced movement planning can be used to draw conclusions about the participants' intentions at that point in time. For this purpose participants perform self paced movements as soon as they feel an intention to move. They are told that a classifier will attempt to predict their movement. In reality this 'classifier' makes predictions based on a normal distribution determined by the participants' previous movement times. Participants are instructed to abort any movement they were preparing as soon as the classifier makes a prediction. After each trial participants are asked whether they felt a conscious intent to move at the time the classifier predicted an upcoming movement.

The information on the participants' intent to move collected by means of self-reports is used to assess whether the brain response to the interruption is quantifiably different when participants had formed a conscious intent to move as opposed to when no such intent was present. In response to a prediction I expect a brain repsonse that resembles an error potential. The timing of the potential is expected to be similar in cases where there was self-reported intent and cases where there was no intent. The amplitude of the potential is expected to differ between cases where participants report an intention to move at the time of prediction as opposed to when they report not having an intention. In cases where the participant moves before a random prediction is made by the classifier I expect no such potential at all.

If the response is indeed related to an error potential I expect a positive peak to occur at around 200 - 500 ms after the participant receives feedback on the prediction [7–9]. Since the error potential is thought to originate from the anterior cingulate cortex and presupplementary motor area [7] I expect the potential to be most visible around electrode Cz. [7, 9]

According to Ferrez et al [7] It is possible to differentiate between different types of error potentials. More specifically, Ferrez et al point out that when in an interaction between a BCI and a participant the BCI makes an error, the resulting error potential is different from that which is observed when the participant makes a mistake. This 'interaction error potential' is characterized by a second negative component, that is not observed after an erroneous response by the participant [7]. If an error potential is elicited after a prediction, then I expect to observe this second peak only in cases when participants do not report having had the intention to move. In those cases the participant may think that the BCI made an error when predicting a movement since the participant was not aware of any movement preparation.

If the brain response to an interruption when participants report having had an intention actually differs from the response when participants indicate having had no intention, then this suggests that movement intention is detectable based on EEG data measured from the brain. This could be used to develop a probing technique to detect whether a person has an intention to move at a certain moment in time, without having to rely on subjective recall or indirect behavioral measures. Instead, a classifier could be trained to distinguish the brain response to a probe when there was an intention to move from cases where there was no such intention. Since such a method would rely entirely on EEG data, I believe that it would be more accurate and faster than methods relying on feedback collected after the fact.

2 Methods

2.1 Participants

The experiment was performed on a small number of participants as a pilot study. Data was recorded from four participants, however due to difficulties with recording only data from three participants was used in the final analysis (two male, one female). The mean age of these three participants is 21.6 years (standard deviation: 3.5 years). All participants were right handed (according to self report) to avoid confounds due to differences in handedness. [10] All participants volunteered for the experiment and gave written informed consent.

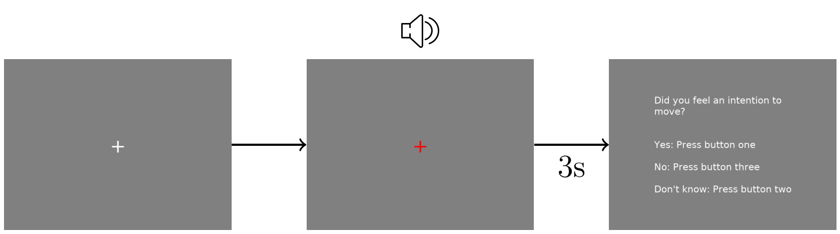
2.2 Task

The experimental setup used for this research is inspired by previous work by Matsuhashi et al [3] and Verbaarschot et al [6]. Participants are instructed to press a button as soon as they feel a conscious intention to move. Movement onset times are completely self-paced and only determined by the participants' intention. Participants are told that a classifier will predict their movements.

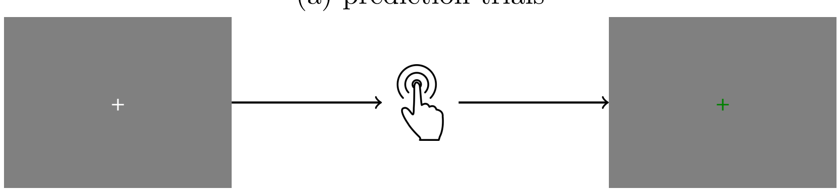
At the start of each trial a white fixation cross appears on screen that participants have to fixate for the duration of the trial to minimize eye movements. If participants press a button the fixation cross turns green for two seconds, after which it turns white again indicating the start of the next trial.

If the classifier predicts an intention to move, the fixation cross turns red and a sound is played. Participants have to abort any movements they were engaged in and are instructed to remain looking at the fixation cross while avoiding to blink. After three seconds a question appears on screen asking participants whether they felt an intention to move at the time the prediction occurred. Possible answers are "Yes", "No", or "Don't know". The third answer possibility is included to not force participants to make a choice in cases where they are uncertain. Further, the button used for each answer is randomized for each trial to avoid that participants already start preparing for a specific button press before the question appears on screen. After participants give an answer the next trial starts immediately.

Participants receive additional instructions stating that apart from hand movements any other movement and excessive eye blinks should be avoided in the time span between a prediction and the prompt asking the participant for feedback.



(a) prediction trials



(b) movement trials

Figure 1: Stimuli used in the experiment

2.2.1 Probe Times

Since the experiment is used to investigate the difference in brain responses to correct and incorrect predictions there is no need to train a classifier to be as accurate as possible. Instead, probe onset times are drawn from a normal distribution of which the mean and standard deviation are determined by previous action times of the participant. The parameters of the distribution are optimized such that ideally one fifth of probes occur more than two seconds before mean movement onset and one fifth of probe times occur later than movement onset times. Additionally all drawn onset times smaller than 2.5 seconds after trial start are discarded since data from such trials would likely be contaminated with artifacts from the previous trial or from the change in color of the fixation cross at the beginning of the trial. Mean movement time and standard deviation of movement times are calculated from the preceding seven movements a participant made. Whenever a participant indicates after a prediction that they did not have an intention to move, the mean of the distribution is artificially increased slightly to avoid frequent predictions that are too early. To adjust the probe distribution a 'fake' observation is added to the list of previous action times. The time of this observation is computed as the mean of the previous 7 actions + 2 seconds.

2.2.2 Procedure

Participants are seated in a chair facing a computer screen. Speakers are placed next to the screen and a button box is placed on the table in front of the participant. The participants are instructed to rest their right hand on the buttons of the button box and to look at the screen in front of them. The right hand should be used to press a button on the button box as soon as a conscious intention to move is felt.

Trials are conducted one after another without interruption to avoid unnecessary delays in the experiment. After each block of 10 trials participants have the opportunity to take a self paced break. The experiment continues when the participant indicates that they want to continue by pressing a button. Participants are instructed to blink during breaks and to avoid blinking and moving as much as possible during recording. Introducing breaks after every 10 trials limits the recording intervals to 1-2 minutes at a time. This is done to avoid fatigue and excessive eye blinks in participants [8]. To avoid fatigue, recording sessions are limited to about 30 minutes per participant, resulting in roughly 20 blocks and 200 trials per participant.

2.3 Data Acquisition

Data is recorded using a Biosemi EEG cap with 64 active electrodes placed according to the 10-20 system [11]. Additionally, EOG data is recorded using four electrodes placed above and horizontal to the eyes and EMG data is collected by placing two electrodes on the wrist and on the extensor digitorum of the participants right arm. Reference activity is recorded from two electrodes on the participants mastoids.

2.4 Analysis

The collected data from trials where the classifier made a prediction is sliced into epochs spanning from three seconds before the prediction to three seconds after the prediction. Choosing a rather large time window ensures that there is a long enough interval before stimulus onset that can be used to correct baseline activity and detrend the data.

The EEG data is re-referenced to a common average reference to remove all noise that is shared between all electrodes. This is done to isolate the brain signal from external noise [12]. The data is demeaned to ensure an even baseline for all electrodes and linear trends are removed. This is done to counteract slow electrode drift. To correct for artifacts introduced by eye movements, signals from the four EOG channels are detrended as well and subsequently EEG data is decorrelated from the EOG signal.

A bandpass filter between 0.3 and 40Hz is applied to EEG channels. This filters out slow drifts in the signal as well as high frequency oscillations that are not relevant to the analysis. All channels where the mean power deviates more than 2 standard deviations from other channels are removed to correct for very noisy channels and faulty electrodes. All trials where the mean power deviates more than 3.5 standard deviations from the mean are removed as they likely represent outliers. Afterwards channel removal is repeated. [6]

For further analysis the data is split into "yes", "no" and "undecided" classes according to participant feedback. Undecided trials are removed from the main analysis. For "yes" and "no" classes ERPs are calculated by taking the average over all trials for a condition. ERPs are calculated for all channels that were not removed during preprocessing.

In addition to the main analysis movement trials are sliced from -2.5 seconds to 2 seconds after a button press and all trials where a movement occurred earlier than 2.5 seconds before trial start are removed to avoid artifacts from previous trials. Preprocessing is conducted as for prediction trials. When plotting the Readiness Potential, the movement data is low-pass filtered at 10Hz since the readiness potential has a low frequency and higher frequencies only obscure the RP.

To assess whether differences between intention and no intention conditions are significant a cluster permutation test is used [13]. This non-parametric test is suitable for multidimensional data such as multi-channel EEG signals since it deals well with the multiple comparison problem [13]. For each participant an ERP is computed per condition. Since the brain response is expected to have the properties of an error potential, only those electrodes for which a relevant signal is expected are included. These channels are located along the midline of the scalp and centered around electrodes FCz and Cz over the motor cortex. Included electrodes are FC1, C1, CP1, CPz, Cz, FCz, FC2, C2 and CP2. This has the added benefit that none of these channels were removed during preprocessing for any of the participants which simplifies comparisons (most electrodes that were removed are on the 'edges' of the cap) Since all participants performed both 'conditions' a within subject setup is used. The test is performed over the relevant time interval for an error potential starting at the time of prediction and extending over 500ms. The sample level statistic used is a dependent t-test and the data is permuted 1000 times using Monte-Carlo sampling. [14]

Additionally, a regularized linear classifier is trained on the prediction trials for each participant to assess whether it is possible to distinguish between intention and no-intention brain responses on a single trial basis.

Large parts of the analysis were conducted using the FieldTrip [15] and buffer_bci (`https://github.com/jadref/buffer_bci`) toolboxes for MATLAB (`http://www.mathworks.com`)

3 Results

3.1 Distribution of Responses and Preditions

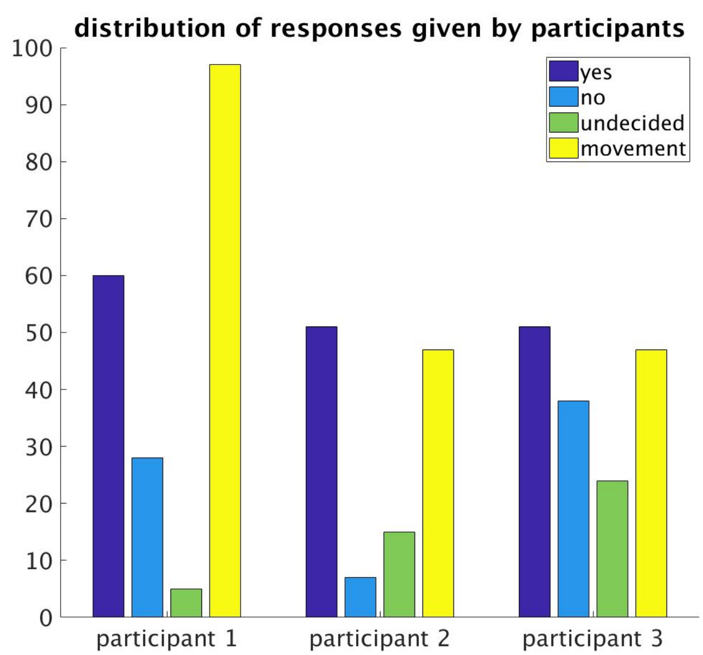


Figure 2: number of responses and movements grouped by participant

For each participant between 160 and 190 trials were collected in total. Interestingly, all participants indicated having had an intention to move in a substantial proportion of trials in which a prediction occurred. Especially participant 2 indicated not having an intention only rarely. Ideally, the yes- and no-condition should have roughly the same number of trials. In this case it seems that using an adapting normal distribution leads to predictions that are 'too accurate' for the purpose of this experiment.
Further, participant 1 performed a movement much more often than the other two participants, which moved the same number of times. While participants 1 and 2 only rarely indicated being unsure about having an intention participant 3 indicated being unsure quite often leading to a larger number of trials that cannot be included in the analysis.

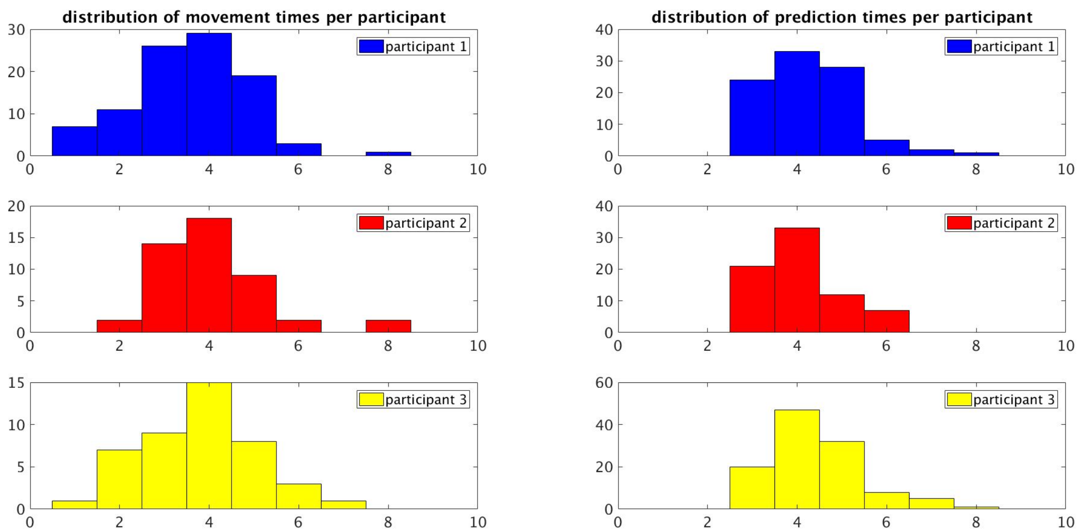


Figure 3: Distributions of movement and prediction onset time relative to the beginning of the trial. Bins indicate seconds after trial start.

Both the timings of movements as well as those of predictions seem to be normally distributed. The distributions appear centered at around 4 seconds after trial start. No predictions occur earlier than 2.5 seconds after trial start - this is by design as such trials would need to be excluded from analysis due to possible artifacts from previous trials.

3.2 Prediction Trials

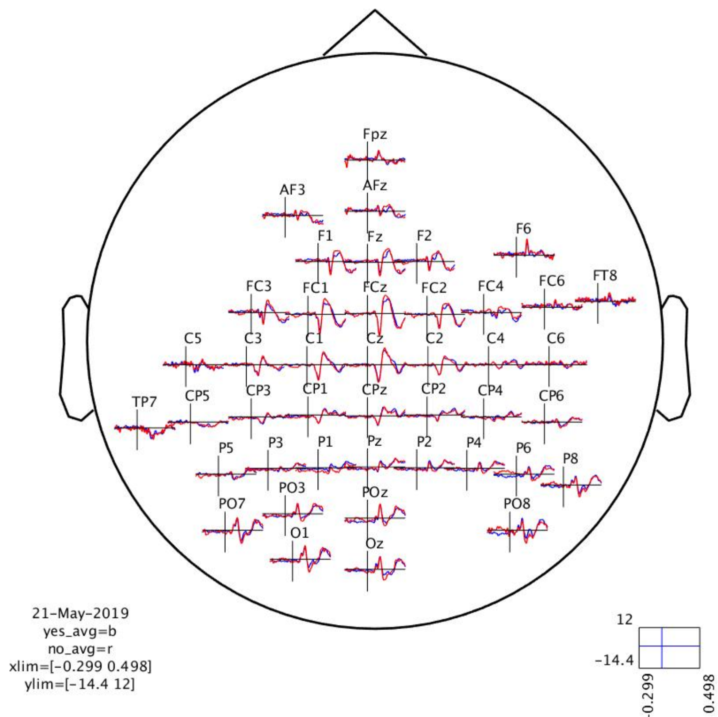
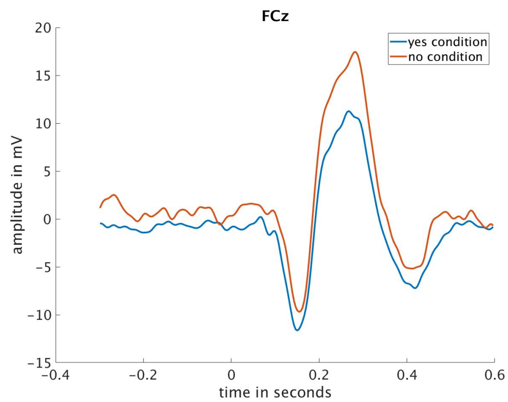
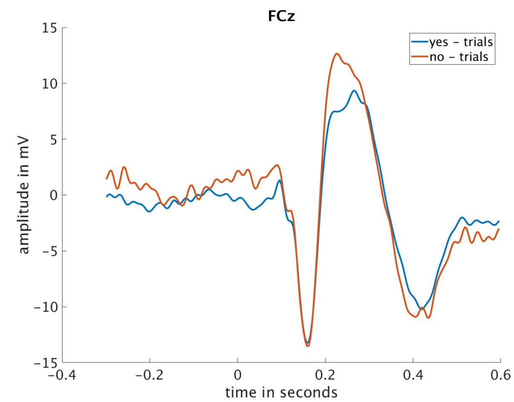


Figure 4: average brain response for participant 1 for trials in which a prediction occurred, included are all EEG channels remaining after preprocessing

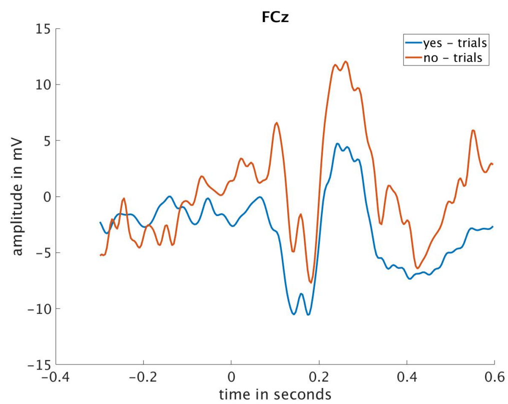
A clear ERP is visible relative to the onset of a prediction for trials where a prediction occurred. The brain response is most clearly visible at electrode FCz and the surrounding electrodes (FC1, FCz, FC2, C1, Cz, C2). The response is characterized by a clear negative peak occurring roughly 160 milliseconds after the stimulus, followed by a second positive peak 250 milliseconds after stimulus onset. There is a clear visual difference in the amplitude of the peak. The deflection is stronger in the "no" condition compared to the "yes" condition. This effect is clearly visible for participant one and three as well as in the grand average ERP computed over all three participants. The ERP of participant two is much less clear than for other participants. This is likely due to there being fewer trials making up the ERP, however a clear difference in the amplitude of the positive peak is still visible.



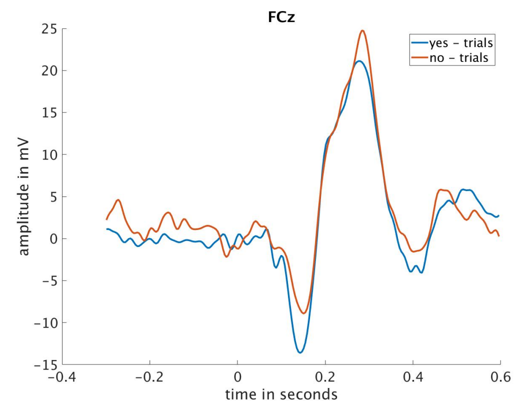
(a) Grand Average



(b) Participant 1



(c) Participant 2



(d) Participant 3

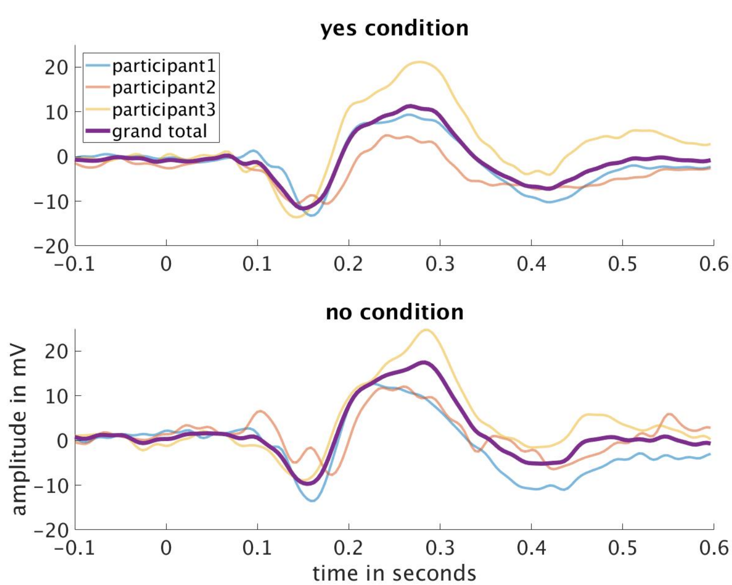


Figure 5: event related potential in prediction trials. Prediction occurred at time 0. Trials are split into a yes (intention) and no (no intention) condition based on self report by participants

In the topographic plots (Figure 6) it is visible that the amplitude changes are largest in the middle of the scalp. This is consistent with descriptions of the location of an error potential [7, 9]. When separating the prediction trials into intention and no intention conditions it is visible that the location of the response is the same in both conditions and that the difference in amplitude of the responses is largest in the same area - over electrode FCz and surrounding electrodes(Figure 7).

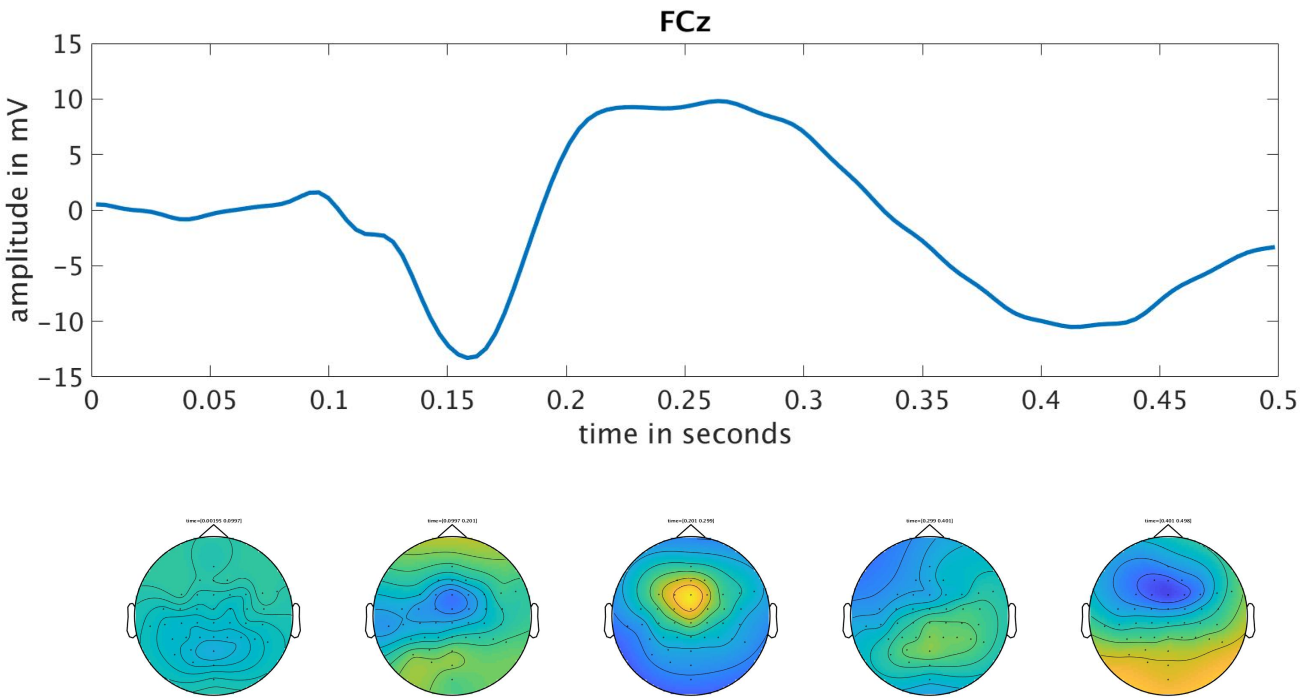
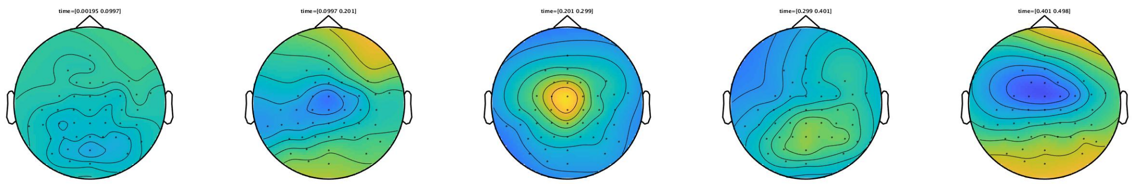
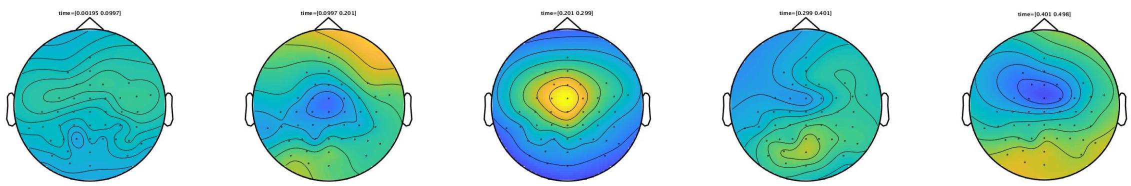


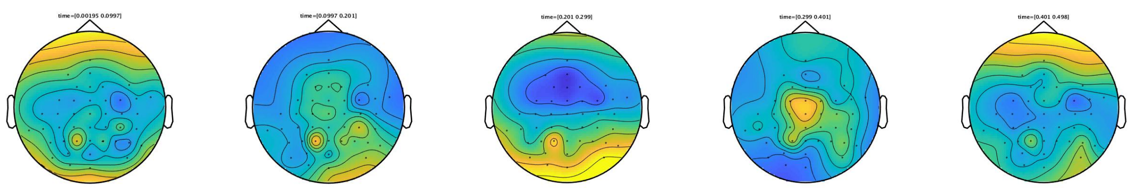
Figure 6: ERP for all prediction trials of participant 1 (*top*) and corresponding topographic plots (*bottom*). Topographic plots are shown for time intervals of 100ms. Clearly visible is the change in activity at times corresponding with the large negative and positive peaks in the ERP (plot 2,3 and 5). The change in activity is largest in the area of the anterior cingulate cortex and presupplementary motor area (centered around electrode FCz)



(a) intention



(b) no intention



(c) yes - no difference

Figure 7: Topographic plots for participant 1 for time intervals of 100ms starting at prediction time and ranging up to 500ms after stimulus presentation. Plots in the first row show the average response for prediction trials in which the participant indicated having had an intention at the time of prediction, the second row shows the average response when the participant indicated not having had an intention. The third row shows the yes-no difference between the two conditions.

3.3 Movement Trials

For trials where the participants performed a movement a readiness potential is visible leading up to the button press. A lateralized readiness potential is visible at electrode FC1. Most notably, the large error potential-like response that is seen after a prediction is not visible in movement trials.

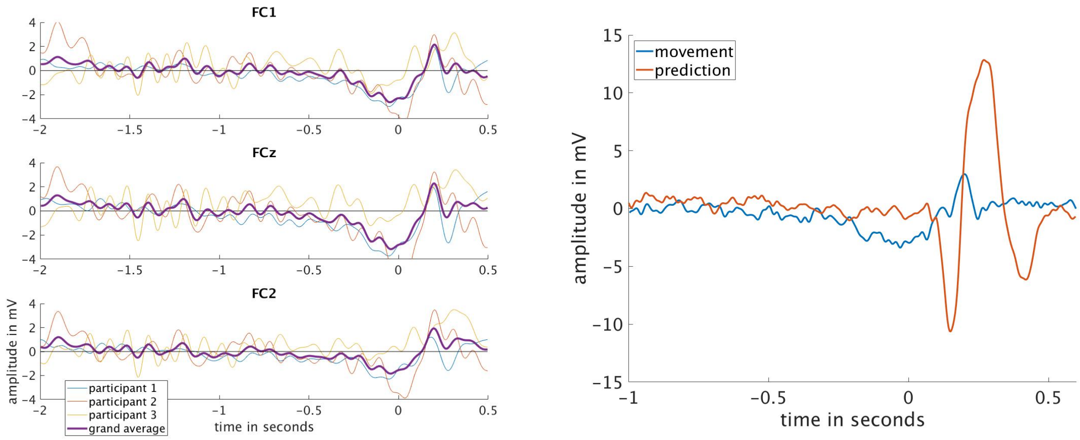
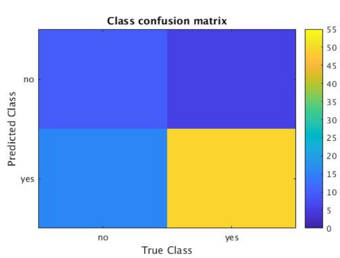


Figure 8: Grand average Readiness Potential at FC1, FCz and FC2 along with Readiness Potentials per participant (*left*). Comparison of grand average readiness potential and response to a prediction at electrode FCz (*right*)

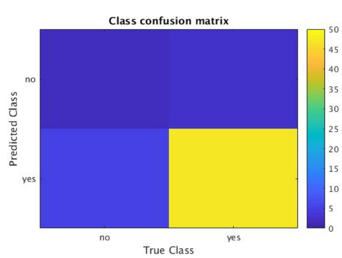
3.4 Statistical Analysis

Results from the cluster permutation test indicate a significant difference between the intention and no intention conditions in the time interval between 416 and 420ms after a prediction at electrodes C1, CP1 and Cz. Other locations and time intervals were not significant.

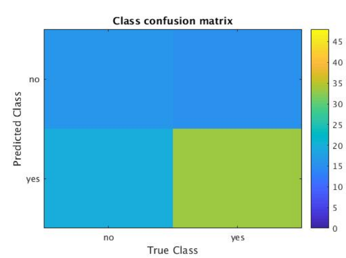
participant	yes	no	performance
participant	55	26	63.7%
participant	50	7	61.3%
participant	48	36	56.6%



(a) Participant 1



(b) Participant 2



(c) Participant 3

Figure 9: Classifier performance per participant and number of instances per class

Classifier performances per participant are listed in the table in Figure 9. performance is barely above chance level (50%) for all three participants. Many 'no intention' trials were falsely classified as 'intention trials' as can be seen from the confusion matrices.

4 Discussion

In the present free movement task a strong brain response has been shown after an interruption in the form of visual and auditory feedback to the participant. Participants were told that a computer would attempt to detect their intention to move and that interruptions were the result of a prediction. It was hypothesized that as a result of this unexpected and unwanted interruption an error potential would be visible in EEG data measured from the participant. Indeed, the response that is measured has the same properties as error potentials previously reported in the literature [7, 9]. The distinct shape of the ERP as well as its location closely match reports about ERPs measured in response to errors.
Further, as expected there is a visual difference between the ERPs computed from trials in which participants indicated an intention to move and those where they indicated no such intention. Especially the amplitude of the large positive peak 250ms after stimulus presentation differs between these two conditions. The peak is stronger when participants indicate not having had an intention. This could be due to the prediction being being less expected by the participant. When participants have formed a conscious intention by the time the prediction occurs, then the prediction may be at least somewhat anticipated by the participant - resulting in a smaller error potential since the perceived error is not as large.

4.1 Statistical Significance

Although it is tempting to interpret these findings as evidence for an influence of conscious intention on the error potential it is important to be careful about the results. The difference between the two conditions was not statistically significant at the times of the two main components of the error potential. Only a very brief interval much later showed significant differences - although roughly at the location where a difference may be expected if it were due to differences in the error potential. This finding is interesting as visually the difference between conditions in this time interval are not very large compared to the difference in the earlier peaks and the direction of the effect seems inconsistent when looking at the ERPs for separate participants. While for participant two and three there is a larger negative peak 400ms after a prediction when participants reported no intention to move, this effect is small and reversed for participant one.

Even though results from the statistical tests do not confirm the visual observations it is not certain that these observations are wrong. Instead a plausible explanation is that there simply is not enough data for the difference to be significant. There is a lot of variability between single trials and when comparing ERPs from different participants the overall amplitude of the ERPs differ widely - despite the direction of the difference between conditions being consistent. This could be due to external effects such as the signal strength as a result of how well electrodes are connected to the participant's skull or different sets of electrodes being used for different participants. To investigate this further, a larger study with more participants and longer recording sessions per participant are needed.

4.2 Classifier Performance

A linear classifier trained on single trials did not seem to find any meaningful distinction between the two conditions for any of the participants. This is not surprising, since the number of trials that are available per participant is very small for all three participants. In addition to this, there is a large class imbalance between the two relevant conditions for all three participants. Since participants indicated having an intention to move more often than not, the classifier is likely biased towards classifying new signals as belonging to the 'intention' class. For participant two especially the imbalance is very large, as there are only seven trials in the 'no intention' class. The corresponding confusion matrix also indicates that a lot of the negative trials were classified wrongly. For the other two participants a similar pattern is visible (Figure 9). Many trials belonging to the 'no intention' class are classified as trials where the participant has an intention.

To combat these issues it may be useful to shift the mean of the distribution governing prediction times in a way that results in more frequent predictions that occur too early for an intention to be present. However, this may not be possible since participants tend to move fairly quickly after the start of a trial (Figure 3). Allowing predictions to follow too quickly after trial start will lead to artifacts in the data caused by the stimulus change at trial start and movements or button presses from the preceding trial. Instead, it would be better if participants were to move at a later time in the trial, but instructing participants on this will likely influence results because the timing of movements will no longer be determined only by the participants own intention to move, but instead will be biased by the instructions given in the experiment.

Alternatively, it is expected that classifier performance will improve if more data is collected for each participant.

4.3 Criticism and Limitations

The experimental design used here has some limitations. First, the experiment cannot be used to infer the time at which a movement intention becomes conscious. This is an obvious drawback of this technique as compared to paradigms as proposed by Libet [2] and Matsuhashi [3]. These studies measure the onset time of conscious intention relative to movement onset. However, in the experiment used here this is impossible. When probed the participant needs to interrupt their movement and thus it is not possible to use the movement time as a fixed point of reference as is done by Libet.

To address this, a follow-up study may assess whether the probing technique used here also elicits the same error potential if participants are instructed to ignore the probe and perform their movement as intended. If the difference in amplitude in the brain response to a probe is also visible in such a setup, then this allows for an experimental setup similar to that used by Matsuhashi et al [3] without the need for participants to interrupt their movements. Such a task may be more intuitive since as opposed to Matsuhashi et al's task the participant does not need to decide whether they were planning a movement at the time a probe is presented. However, for such a setup it is also necessary that a classifier can reliably distinguish between intention and no-intention trials on a single trial basis. With the current data this is not possible.

One limiting factor for comparing results from the present study with results from previous research on error potentials is that in many cases the error potential is shown as a difference wave between a condition where an error occurred and a condition where no error occurred [7, 9]. Constructing this difference wave leads to all brain activity shared between conditions and therefore not related to an error being excluded. For results from the present experiment such a difference wave cannot easily be constructed since in both conditions of interest ("intention" and "no intention") an error response is expected. Using the difference between the ERP for predictions and the ERP for a successful movement is also not a good alternative, since a readiness potential occurs for movement trials. Therefore it should be kept in mind that while commonly error potentials are shown as difference waves this is not the case here. As a result the 'error potentials' in this paper may contain some components that are an effect of a brain process not related to perceiving an error.

5 Conclusion

The experiments performed suggest that it is possible to infer whether a participant had an intention to move at a certain point in time by presenting a visual and auditory probe. However, based on the present data it is not possible to reliably detect an intention to move in single trial data. A classifier trained on the data did not reliably distinguish trials where an intention was present from those where there was no intention. Further, the main findings are not well supported by the results from statistical analysis. .Both of these points of criticism may be addressed by conducting a larger scale study and by collecting larger amounts of data.

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6 Appendix

Included are plots of the results from participants two and three that were not shown in the main document:

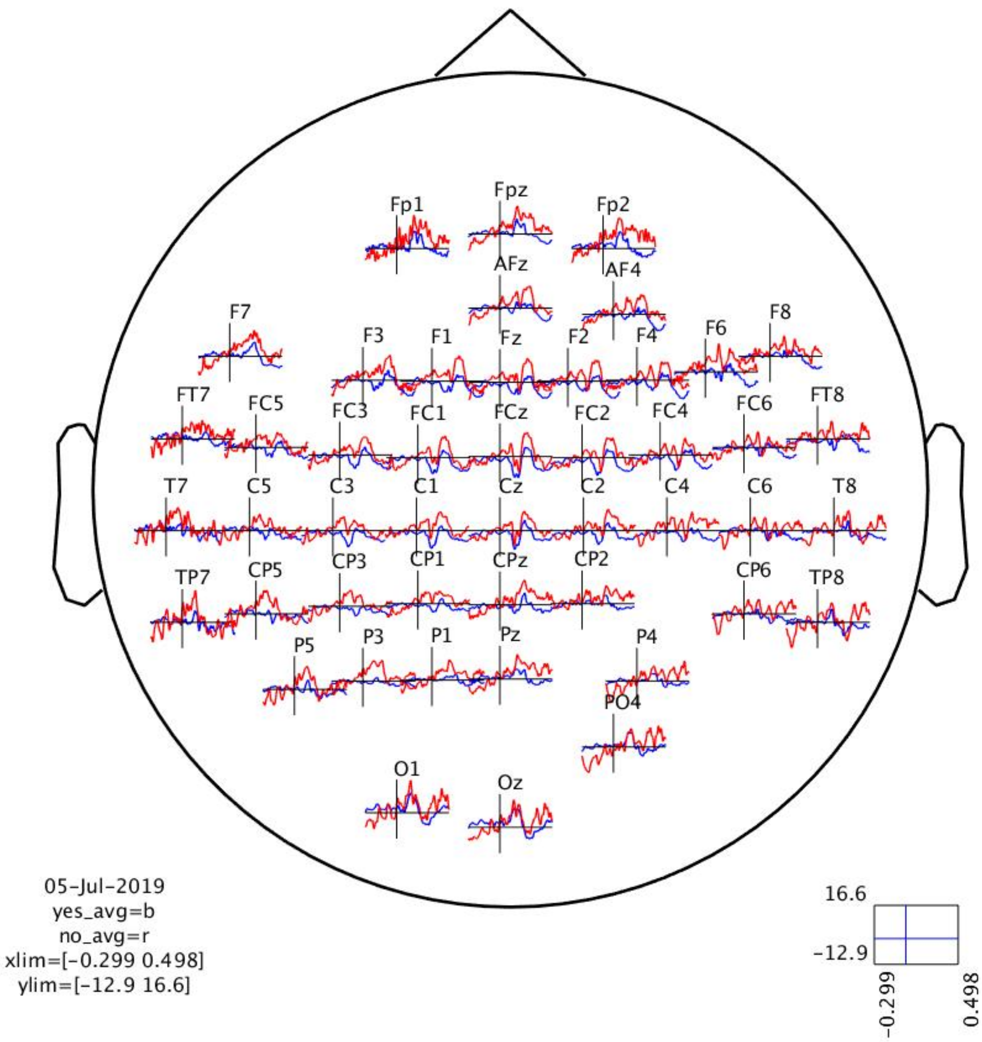

Figure 10: average brain response for participant 2 for trials in which a prediction occurred, included are all EEG channels remaining after preprocessing. The data is split into two conditions: The average for trials where after a prediction the participant indicated having had no intention to move is indicated in red, the average of those trials where the participant did report an intention to move is indicated in blue

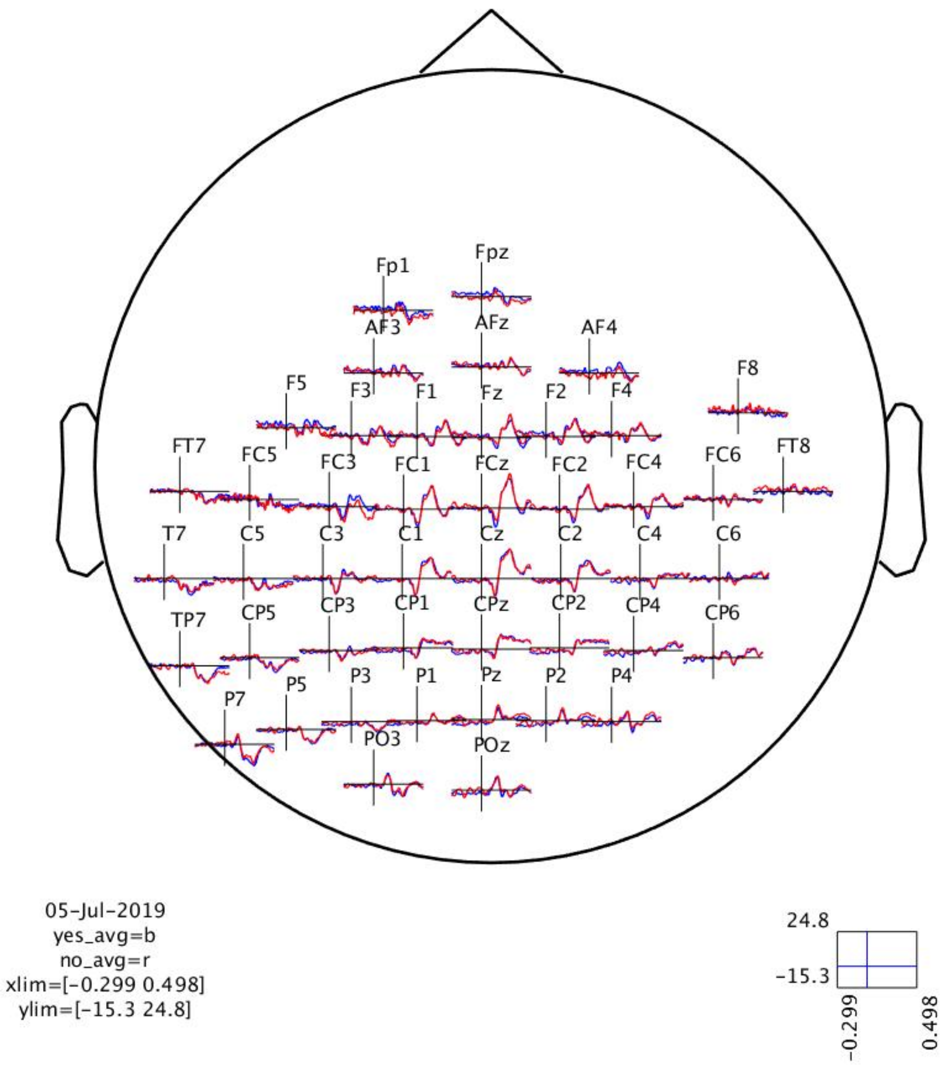

Figure 11: average brain response for participant 3 for trials in which a prediction occurred. Indicated are the average of the "intention" and "no intention" conditions as indicated for Figure 10

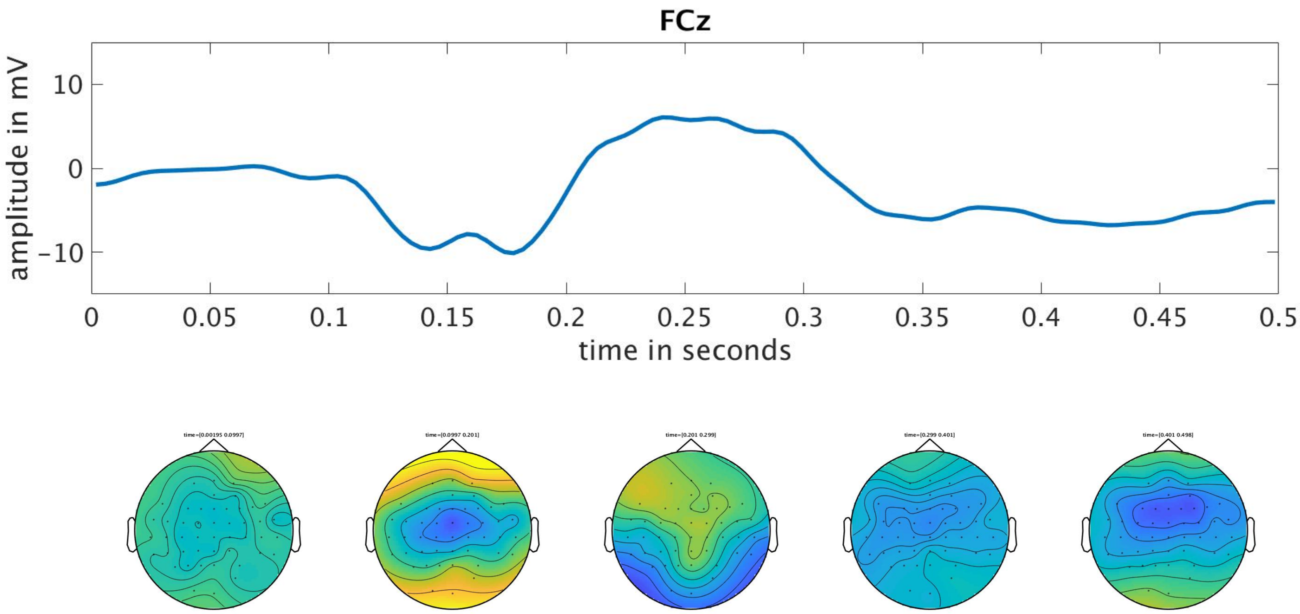

Figure 12: ERP for all prediction trials of participant 2 (*top*) and corresponding topographic plots (*bottom*). Topographic plots are shown for time intervals of 100ms.

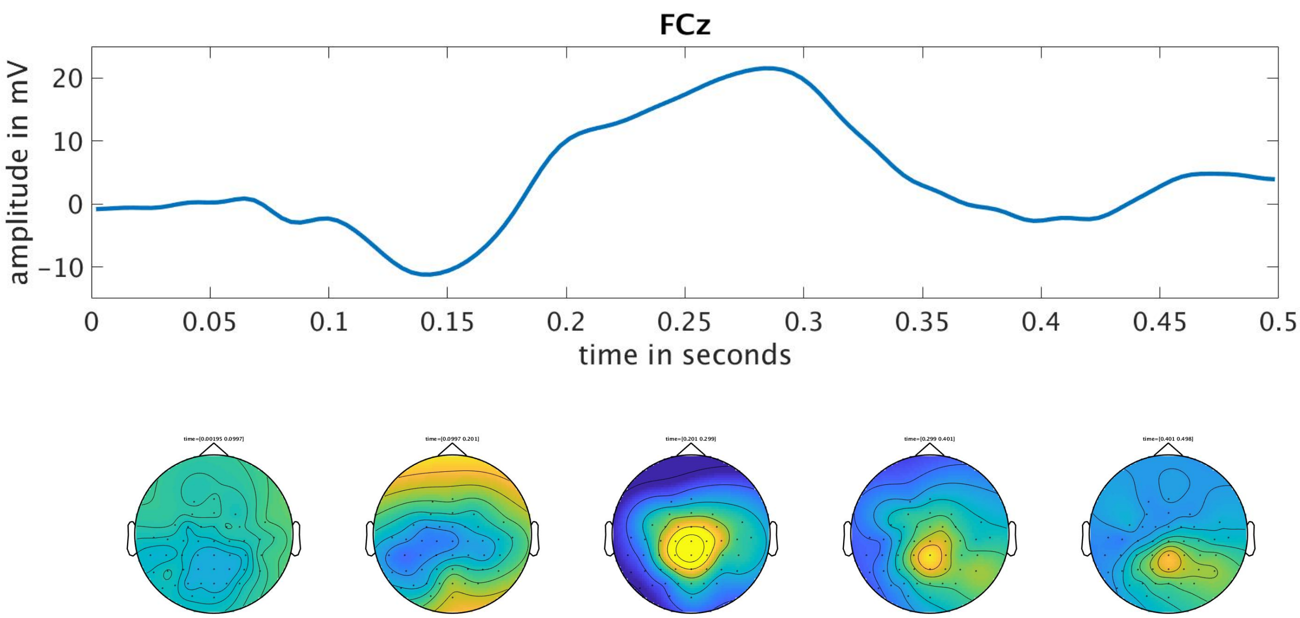

Figure 13: ERP for all prediction trials of participant 3 (*top*) and corresponding topographic plots (*bottom*). Topographic plots are shown for time intervals of 100ms. Note: electrode locations may not be entirely accurate due to channels being removed during preprocessing