# Examination of the P300 Wave and Correlation Topographies for Standard vs. Oddball

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*Abstract*—**Brain-computer interfaces (BCIs) like the P300 speller are a direct connection between brain signals and an external computer. The speller lets a user type words by focusing on letters on a screen. Focusing on the oddball letter creates a P300 wave, which was observed in the evoked potentials. The correlation plots and correlation topographies created in MATLAB show the highest correlations between the stimulus type (oddball or standard) and the signal amplitude at about 250-300ms and in the channels towards the center of the head. This is supported by the analysis of the selected individual channels. This analysis supports the oddball paradigm and shows how the P300 speller can operate.**

*Index Terms*— **Electroencephalogram, Event-related potential, P300, Brain-computer interface, Oddball paradigm, Correlation**

## I. Introduction

BRAIN-COMPUTER interfaces (BCIs) are a direct connection between brain signals and an external computer. One application of this technology is the P300 speller, which allows the user to type words by focusing on letters in a matrix. This device is used to assist people with severe motor neuron diseases that have lost their movement abilities, but not their cognitive function. The device records electroencephalogram (EEG) signals from the user using non-invasive surface electrodes; EEG signals are used for their good temporal resolution and ease of processing and classification [1]. It detects an event-related potential (ERP), a voltage fluctuation in the EEG signal in response to an external stimulus. It works using the oddball paradigm: if a person is exposed to an unexpected, or “oddball”, stimulus, a positive wave of activity will show in the EEG signal at around 300ms after the stimulus, hence the name P300 [2,3]. When the user sees their desired character flash on the screen, the P300 wave will appear in the EEG signal, which the computer will detect and type that character.

For the P300 speller to operate correctly, the device needs to be able to differentiate between a standard EEG signal (not the desired character) and a P300 wave (the desired character). For this classification, learning algorithms such as the support vector machine have been used [3]. In this paper, however, the signals have already been classified. Nonetheless, the P300 wave will be observed graphically and the correlations between the classification and the signal amplitude will be calculated.

Another important consideration is the different EEG channels. Some regions of the brain make the P300 wave more clearly than others; the central and occipital lobes usually form the stronger wave, and the temporal and frontal lobes form the weaker wave. In order to improve the clarity of the wave, the electrodes that carry the weaker signal need to be rejected. The best signals are not necessarily adjacent and choosing the best electrodes and putting them together does not always lead to good results [3]. In order to account for these differences, several channels will be examined individually, and the correlation topographies will be graphed. Finally, waveform morphology in an oddball task is known to vary from individual to individual [4]. This is why the EEG recordings from two subjects will be analyzed.

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## II. Materials And Methods

The software utilized to plot the evoked potentials, the correlations between the classification and the signal amplitude, and the correlation topographies was MATLAB 2020.

### A. Data

The data used in this paper were collected from subjects performing a BCI P300 speller task. In this task, the user was


Fig. 1. The user display for the BCI P300 speller task (right). For each character, all rows and columns in the matrix were intensified a number of times (e.g., the third row in this example).

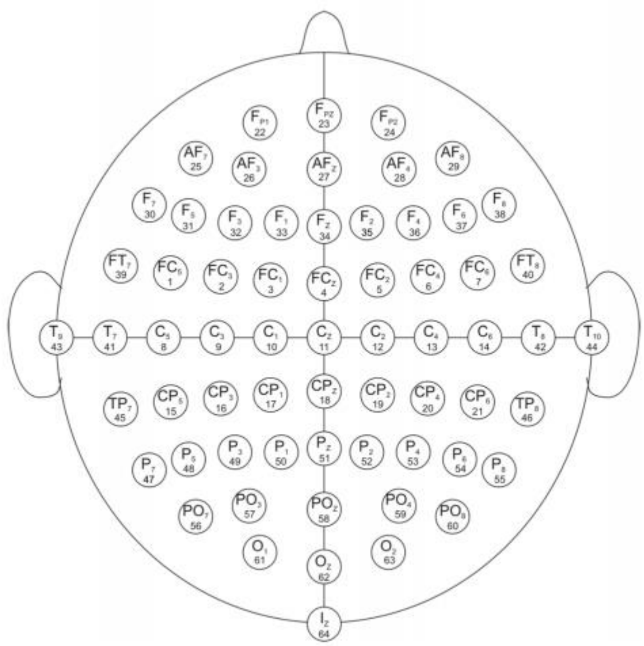

Fig. 2. The electrode designations and channel assignment numbers used to record the EEG signals analyzed.

presented with a 6 by 6 matrix of characters as seen in Fig. 1. In each run, the subject focused on a series of characters to spell the given word. For each character epoch in the run, the matrix was displayed for a 2.5s period with all of the characters at the same intensity. After this, all rows and columns of the matrix were successively and randomly intensified for 100ms at a rate of 5.7Hz. The intensification of the row and column containing the character caused a P300 wave in the user's EEG. After intensification of a row/column, the matrix was blank for 75ms. Any specific row/column was intensified 15 times and thus there were 180 total intensifications for each character epoch. After each character epoch, the matrix was left blank for 2.5s.

The EEG signals of the two subjects were recorded using BCI2000 software and through 64 channels at standard locations designated in Fig. 2. All 64 channels were referenced to the right ear, bandpass filtered (0.1–60 Hz) and digitized at 240 Hz.

The nine runs for each subject were contained in separate files. In total, the EEG data were organized into a 315954 x 64 matrix, with each row corresponding to a time sample and each column corresponding to an electrode channel. Each sample is coded according to the variables in the provided "states" structure. The following variables were used for analysis: states.Flashing is 1 when the row/column is intensified and 0 when it is not; states.StimulusCode is 0 when no row/column is intensified and 1-12 for the row/column being intensified based on Fig. 3; states.StimulusType is 0 when no row/column is being intensified or the intensified row/column does not contain the desired character and is 1 when the row/column does contain the desired character. Finally, important values associated with the recordings are stored in a structure named "parameters". The signal, states, and parameters variables were loaded into MATLAB using the provided load_data() function. For all of the 64 channels, 800ms of signal samples after the start of each intensification was collected, or when states.Flashing changed from 0 to 1 using for loops and if/else statements. The for loops were used to cycle through the 64 channels and each of the time samples. These 800ms samples were used in the later analyses.

### B. *Evoked Potential Plot Creation*

While the 800ms samples were being collected in the for loops, an if/else statement was used to separate the samples for standard signals (states.StimulusType = 0) and for oddball signals (states.StimulusType = 1). The means of these separated samples for each time point were found. Since the signal was digitized at 240Hz, the time vector was from 0ms to 800ms in 1/240s intervals. The standard signal means and the oddball means were plotted on the same graph against the same time vector in order to see the P300 wave. This process was repeated individually for channels 11, 51, 56, & 60 to examine them separately. This process was the same for the second subject.

### C. *Correlation Calculation and Plot Creation*

The correlation between the stimulus type, standard or oddball, and the signal amplitude for each time sample was calculated using corrcoef() in a for loop. The function corrcoef() returns a correlation matrix, so the correlation value (r) had to be extracted for each time sample. Finally, to get positive values and the coefficients of determination, the r values were squared. Both the r and $r^2$ values were plotted against the same time vector from the previous section. These correlations were calculated to see at which time points the user's EEG response best matches whether the desired character was in the row/column. The EEG voltage should be higher when the desired character is flashed and be higher around 300ms due to the P300 wave, and thus the correlations for the time samples around 300ms should be higher. This was


Fig. 3. Assignment of state.StimulusCode values to the rows and columns of the matrix (left).

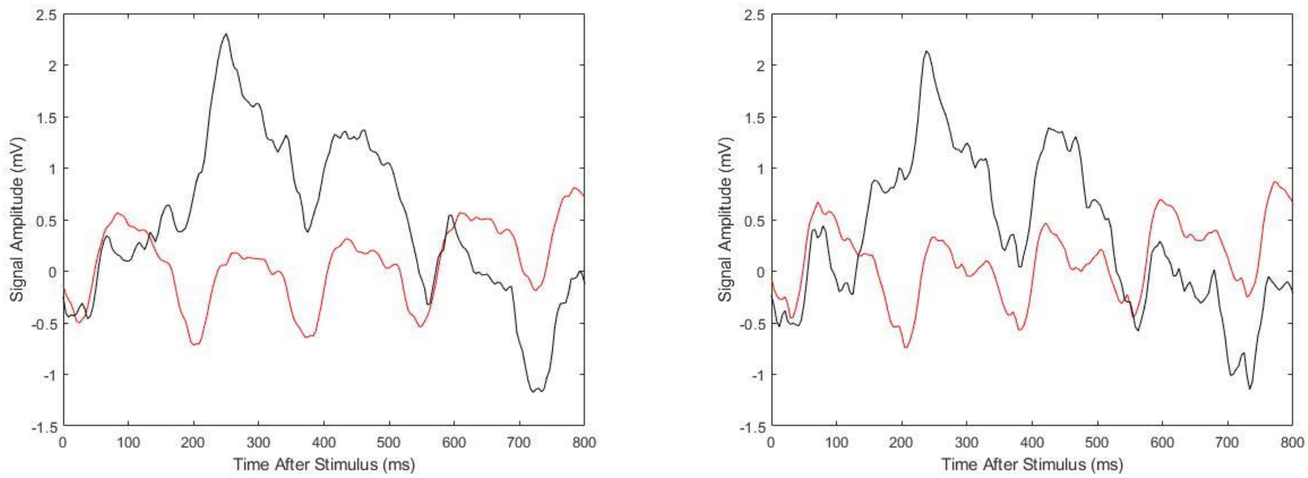


Fig. 4. The evoked potential plots for subject 1 (left) and subject 2 (right). The red lines correspond to the standard response, or when the desired character was not flashed. The black lines correspond to the oddball response, or when the desired character was flashed.

repeated for the channels 11, 51, 56, & 60 to examine them separately. This process was the same for the second subject.

### *D. Correlation Topography Creation*

The correlation values ($r^2$) for each time point from 100ms to 500ms in 100ms intervals and for each channel were gathered using for loops and the corr() function. These time points' topographies were plotted using the provided topoplotEEG() function. These topographies should show at what time point and in what region of the brain the P300 wave is the strongest. This was repeated for the second subject.

## III. Results

### *A. Evoked Potential Plots*

The evoked potentials for all of the channels for standard vs. oddball stimuli for each subject can be seen in Fig. 4. As expected, the wave morphologies differ between the two subjects. The potentials for the undesired/standard characters were smaller in magnitude and more periodic than those for the

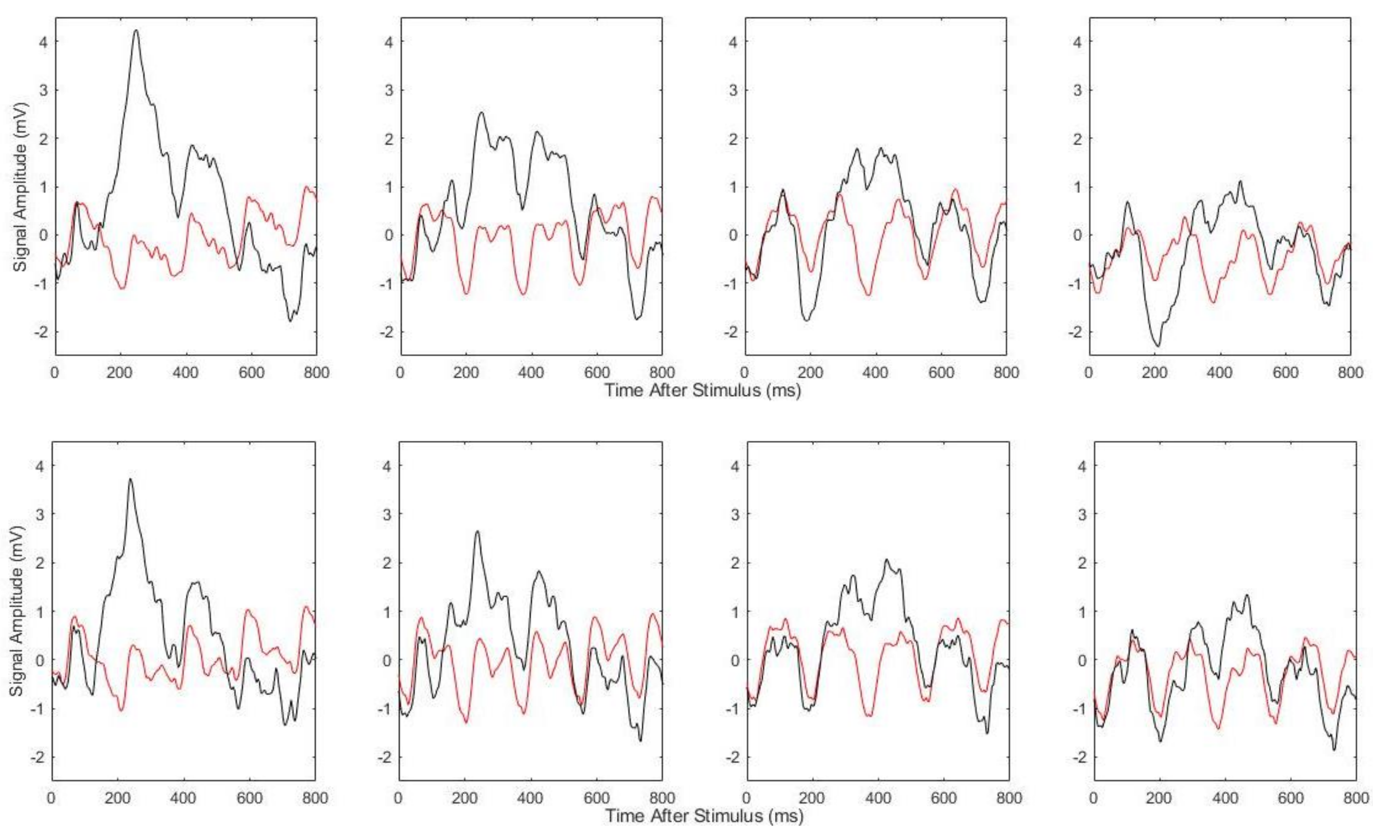


Fig. 5. The evoked potential plots for channels 11, 51, 56, & 60 (left to right) and subject 1 (top) and subject 2 (bottom). The red lines correspond to the standard response, or when the desired character was not flashed. The black lines correspond to the oddball response, or when the desired character was flashed.

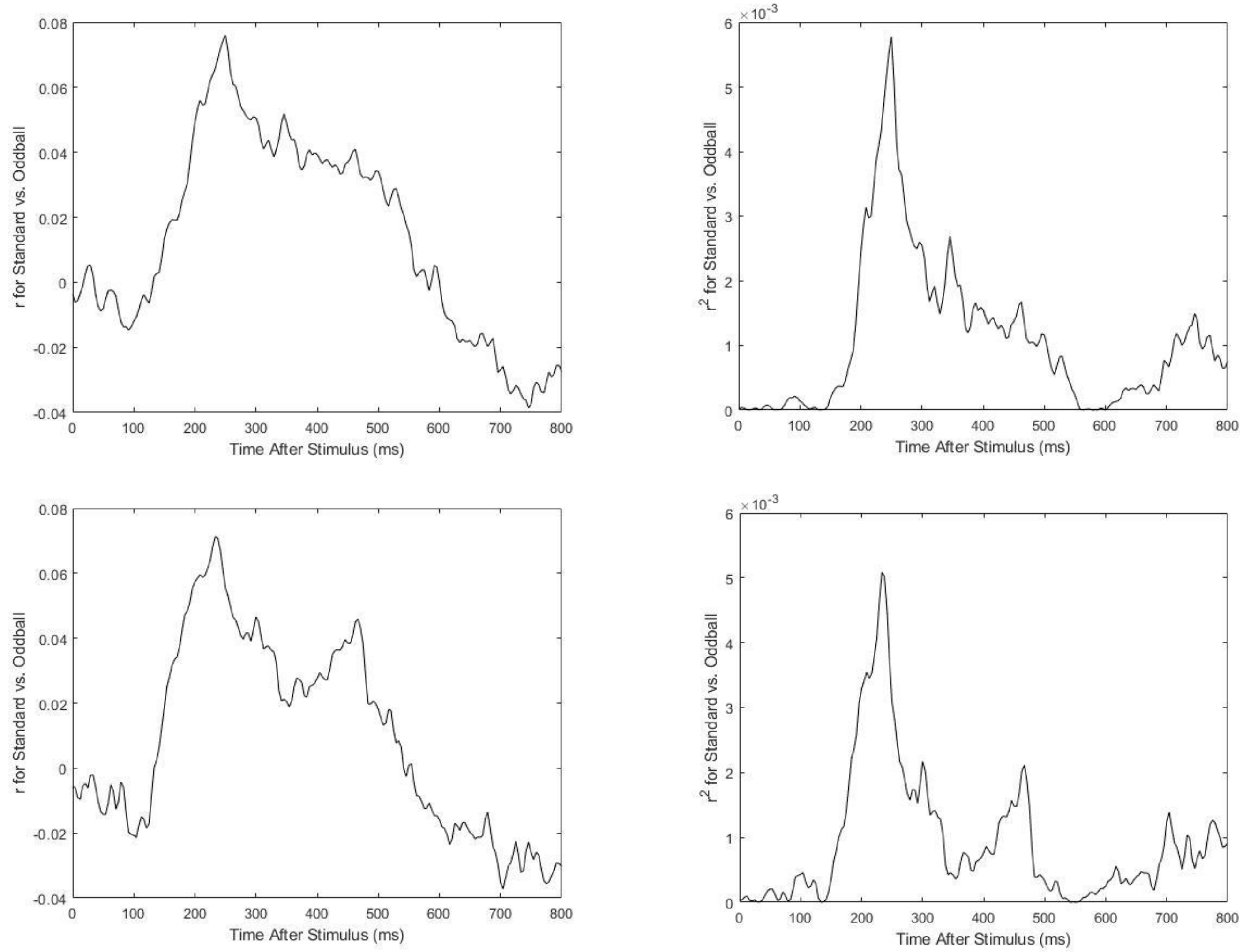


Fig. 6. The r (left) and $r^2$ (right) plots for subject 1 (top) and subject 2 (bottom). The correlation between the stimulus type, standard or oddball, and the signal amplitude is highest around 200-300ms.

desired/oddball characters. The oddball lines have peaks around 300ms, resembling a P300 wave. These peaks are about 2mV above the standard potential at the same time. Interestingly, there are secondary peaks around 450ms.

The evoked potentials for channels 11, 51, 56, & 60 for both subjects can be seen in Fig. 5. Similar to the overall evoked potentials, the P300 wave can be seen for the oddball characters in all of the selected channels. However, the wave is much stronger in channel 11, and to a lesser extent channel 51, than in the other channels. The peaks in channel 11 is about 3.5-4mV above the standard potential, higher than those for the overall. The weaker channels like channel 60 should not be used in the P300 speller as they can hamper the clarity of the P300 wave used to select the correct character to type.

### *B. Correlation Plots*

The correlation plots, both r and $r^2$, for both subjects can be seen in Fig. 6. A higher correlation implies a better distinction between undesired and desired characters. The correlations were highest around 200-300ms, which is expected since this is when the user responds to the flashing character and when the P300 wave begins. Some negative correlations were calculated, showing that at -some points the there was a higher amplitude for the undesired character (stimulus type = 0) than for the desired character (stimulus type = 1) for these time points. This makes some sense before the person has registered the stimulus (before ~200ms) as their neuronal activity should be about the same whether the row/column flashing has the desired character or not. Thus, it can be higher for stimulus type = 0 due to noise or random activity. It also is reasonable for this to happen later after 600ms. After seeing the desired character (and the machine registering it), the subject is no longer focused on that row/column, so the amplitude drops. It will drop lower than if they did not see their character because they are not anticipating it anymore.

The correlation plots, $r^2$, for channels 11, 51, 56, & 60 for both subjects can be seen in Fig. 7. Similar to the overall correlation plots, the correlations are highest from 200-300ms. However, there is a lot of variety between the channels. The correlation peaks are highest for channel 11 and lowest for channel 60. This implies that channel 11 shows a clearer distinction between undesired and desired characters than the other channels. Thus, channel 11 should be used for the P300 speller and channel 60 excluded.

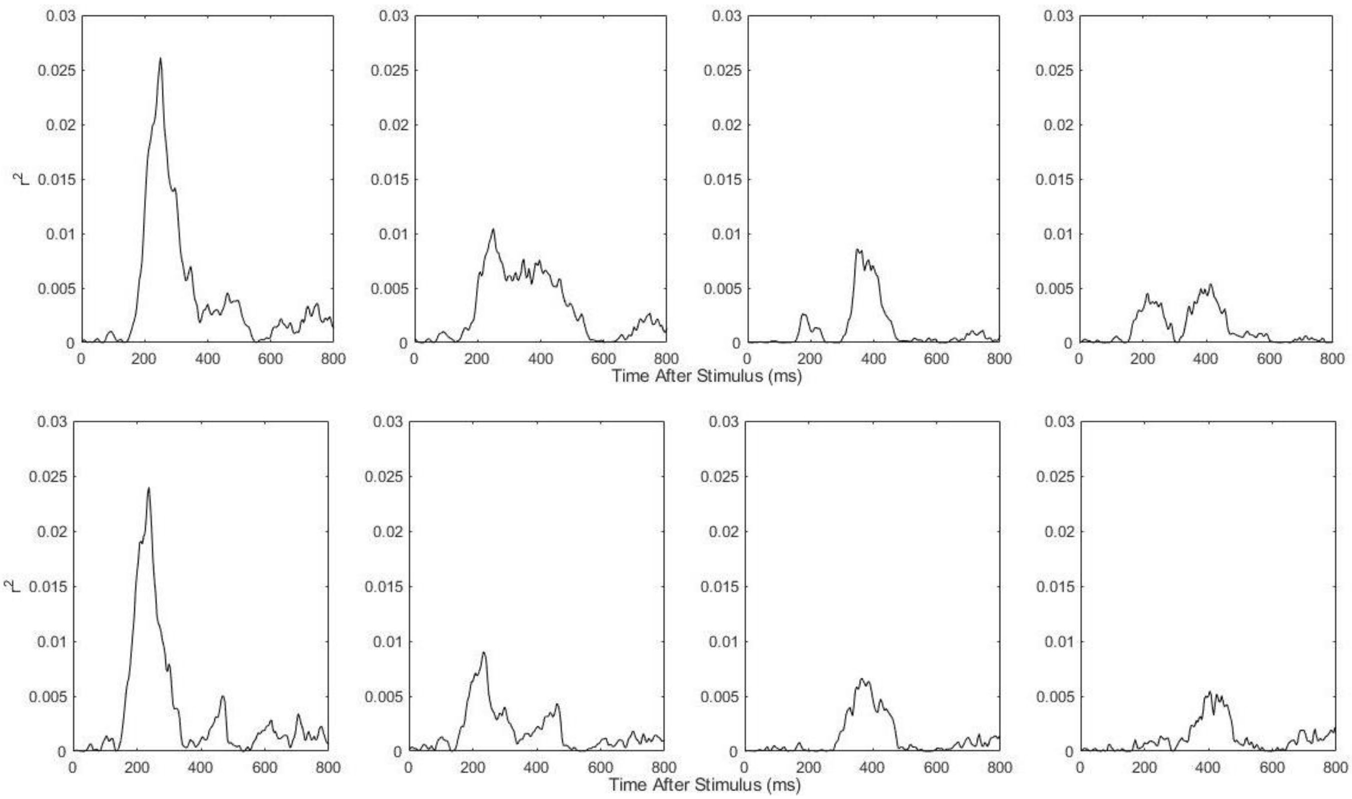


Fig. 7. The $r^2$ plots for channels 11, 51, 56, & 60 (left to right) and subject 1 (top) and subject 2 (bottom). The correlation between the stimulus type, standard or oddball, and the signal amplitude is highest around 200-300ms but differs much between the channels.

### *C. Correlation Topographies*

The correlation topographies for the time points from 100ms to 500ms in 100ms increments for both subjects can be seen in Fig. 8. The highest correlations appear to be at times 200ms and 300ms. It is interesting that the higher correlations appear later for subject 1 as opposed to subject 2. As expected, the correlations, and thus the P300 waves, are strongest in the central and occipital lobes. This matches the data from the previous section, as the channel 11 electrode is located in the center of the head and had a high correlation. Conversely, the channel 60 electrode is located towards the edge and had a low correlation.

## IV. Discussion

The P300 wave was observed in both subjects in the data samples where the desired character was flashed. For both subjects, the wave peaked around 250-300ms. Additionally, there was a second, weaker peak around 450ms. This peak may show a delayed response or reaffirmation of the desired character by the user. Despite the differences between the subjects, there is a clear distinction between the undesired and desired characters, which is necessary for the function of the P300 speller. The time location of this difference is better visualized with the correlation/$r^2$ plots. The correlation peaks appear closer to 250ms, but there are still high correlations at 300ms. As for the brain locations and electrodes, the correlation topographies visualize the areas with the strongest P300 waves. The evoked potential and correlation plots for the

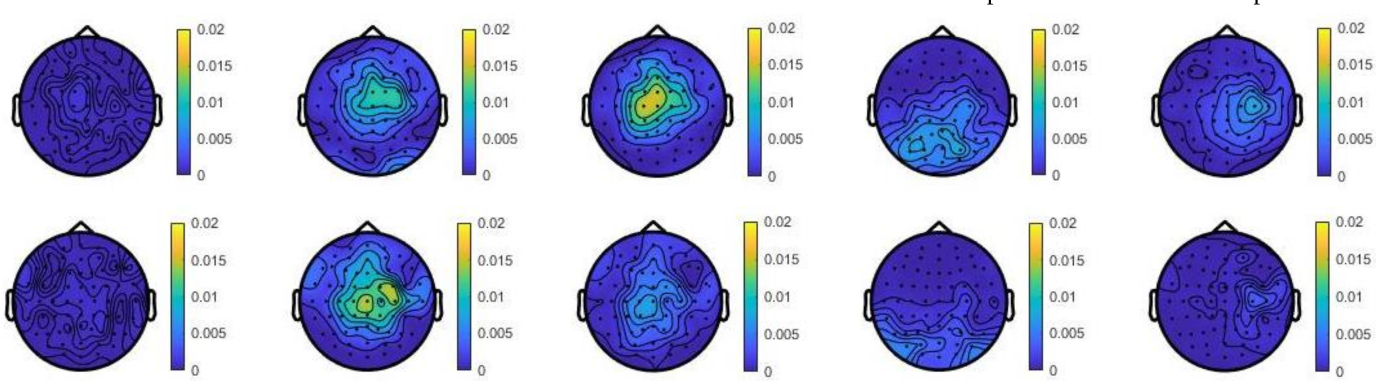

Fig. 8. The correlation topographies for the time points from 100ms to 500ms in 100ms increments (left to right) for subject 1 (top) and subject 2 (bottom).

individual channels support the topographies. Overall, channel 11 was one of the best and channel 60 one of the worst. The data points to the central electrodes getting the best results. Further calculations with only these electrodes will need to be done.

There are several technical and practical issues that were not addressed in this analysis. The need for several flashes of the rows and columns limits the typing speed of the speller [1], although the speed of communication is not as important as its reliability very existence [4]. The EEG recordings provided were done in a laboratory setting. Moving to a home setting introduces many sources of noise, including respirators that the user may need to use [4]. Another consideration is the presence of auditory distractions, which may draw the user's attention from the spelling task [5]. Plus, the interface's color contrast needs to be considered as the speller may be used in different lighting conditions [6]. With users that are unable to speak or otherwise communicate without the speller, it needs to be determined whether the user understands the instructions and can attend to the task; a simpler oddball task must be used for this [4]. There are also different oddball paradigms that can be used rather than the 6x6 character matrix, such as a 3-D virtual keyboard with three rows, three columns, and three depths [2], auditory stimuli instead of visual [7], four choices of "Yes," "No," "Pass," and "End" [4], and hybrid paradigms [1].

Nonetheless, this analysis shows strong support for the oddball paradigm and thus for the viability of the P300 speller device.

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