Project 1: P300 Speller

## Introduction

Individuals without the ability to speak or use their hands to write must rely on others to take care of them and guess their needs. With a P300 Speller program, such individuals would only need the use of their eyes to communicate with others. Users connected to an EEG headset will watch a 6x6 grid of letters and numbers which will flash either an entire row or column (RC) every 100ms. The P300 EEG signal which is a positive deflection of the signal which peaks approximately 250-500 ms after the onset of a target stimulus (Polich J., 2007) can be used to determine when a RC flash with the character the user is looking at occurs. This code takes information from data used to train the P300 speller which can be used to determine when the P300 Speller flashes contain the target character or not. Using this information, the channels which provide the strongest target specific P300 (P3b) signals compared to target nonspecific P300 (P3a) signals can be determined. The N2 signal is also a prominent signal which is defined as a negative deflection from approximately 200-300 ms after a task relevant stimulus (Warren et al., 2011). Channels with the strongest N2 signals can also be identified. Once determined, the information from these channels can be used to determine what character a user wishes to spell, allowing them to type and therefore communicate, using only their eyes.

## Methods

*2.1: Data*

Data used was collected in Guger et al. (2009). Subject files with IDs 3 through 10 were run through the code as they were collected using the RC method whereas subject IDs 1 and 2 flashed only a single character at a time. Voltages were not defined by Guger et al. (2009) but are assumed to be in uV. Five total channels were excluded due to voltages ranging from 20 to -20 uV (subject 4 channels at indexes 4 and 5) or for having voltages ranging from 40,000 to -40,000 (subject 4 channels at indexes 6 and 7 as well as subject 5 channel at index 4).

*2.2: load_and_epoch_data*

Requiring the two inputs *subject* and *data_directory*, this function will load the training data for the desire subject, epoch the data, and return the following variables: *eeg_epochs*, *eeg_epochs_target*, *eeg_epochs_nontarget*, and *erp_times*. The input *subject* is an int equal to the ID of the subject file being loaded and epoched, and *data_directory* is a string with the file path to the subject files. The returned variables *eeg_epochs*, *eeg_epochs_target*, and *eeg_epochs_nontarget* are all ExCxS arrays and *erp_times* is an array with size S where E = number of epochs, C = number of channels, and S = number of samples. Epochs start 0.5 seconds before the onset of an RC flash and end 1 second after. The variable *eeg_epochs* contains all target and nontarget epochs while *eeg_epochs_target* and *eeg_epochs_nontarget* contain only target or nontarget epochs respectively.

*2.3: resample_data and bootstrap_eeg_erp*

The function *resample_data* takes the inputs *input_data* which is an ExCxS array and *number_iterations* which is an int and returns the mean of the resampled data in a CxS array. A number of epochs equal to *number_iterations* is randomly selected from *input_data* with the possibility to randomly select the same epoch more than once into an ExCxS array. The mean of that array is then returned as the output as a CxS array. Due to the random nature of resample_data, any attempts to perfectly replicate the significance plots below will be near impossible, but the overall shape should be relatively similar.

Using *resample_data*, *bootstrap_eeg_erp* takes the inputs *eeg_epochs*, *eeg_epochs_target*, and *eeg_epochs_nontarget* as listed above as well as *bootstrap_count* which is an int to create a resampled set of absolute value differences which will later be used to test the null hypothesis that the target ERPs are not significantly different from the nontarget ERPs. It does this by using *eeg_epochs* which contains all target and nontarget epochs combined as *input_data* to resample a bootstrapped target mean array and bootstrapped nontarget mean array, and finding the absolute value difference of the two bootstrapped mean arrays. The number of epochs in the *eeg_epochs_target* and*eeg_epochs_nontarget* arrays will be used as the *number_iterations* input for *resample_data,* accounting for the inherent difference in size between the original two arrays. Returning the array *bootstrapped_distribution* with dimensions BxCxS where B = *bootstrap_count*, *bootstrap_eeg_erp* will find an absolute value difference between the resampled target and nontarget data a number of times equal to *bootstrap_count*.

*2.4: find_sample_p_value and p_value_fdr_correction*

After completing bootstrapping, the level of significance at each timepoint for each channel can be determined with *find_sample_p_value* which takes the inputs *bootstrapped_distribution*, *eeg_epochs_target*, *eeg_epochs_nontarget*, *erp_times*. To test our null hypothesis that the target ERPs are not significantly different from the nontarget ERPs, the absolute value difference of means between *eeg_epochs_target* and *eeg_epochs_nontarget* was tested against each bootstrapped absolute value difference from *bootstrapped_distribution*. For each channel at each timepoint, the value of the real absolute value difference was compared with the bootstrapped absolute value difference, and the percentage of the bootstrapped values that the real value was larger than was returned as a p value in the output *epoch_diff_p_values* which is a CxS array with p values for each sample at every time point.

Each p value was corrected for multiple comparisons using the *p_value_fdr_correction* function with the inputs *epoch_diff_p_values* and *alpha* which is a float with a default value of 0.05. This function takes the p values from *epoch_diff_p_values*, corrects them, and returns *significant_plot_samples*, *corrected_p_values*, *is_significant_int* which all have the dimensions CxS. The correct p values are returned in *corrected_p_values* at each sample point. Using *alpha* to determine what is considered significant, *is_significant_int* has a value of 1 where the p value of *corrected_p_values* <= *alpha* and a value of 0 otherwise. Used later in a plot, *significant_plot_samples* has a value of 0 where *corrected_p_values* <= *alpha* and a value of None otherwise.

*2.5: calculate_and_plot_confidence_intervals and plot_significant_p_values*

These two functions plot the mean target and nontarget event-related potentials (ERPs) per channel and put all the plots into a single subplot. The function *plot_significant_p_values* takes the inputs *eeg_epochs_target, eeg_epochs_nontarget, significant_plot_samples,* and *erp_times* as described above while *calculate_and_plot_confidence_intervals* takes all of the same inputs except for *significant_plot_samples*. Both functions take *eeg_epochs_target* and *eeg_epochs_nontarget*, find their mean values, find the 95% standard error margin, and plot the target and nontarget data against each other with the added benefit of plotting a point each time the difference between the target and nontarget data is significantly different in the *plot_significant_p_values* function by using the information from *significant_plot_samples*.

*2.6 analyze_across_subjects and plot_significance_across_subjects*

To reduce the impact of artifacts on the data, the function *analyze_across_subjects* runs the *load_and_epoch_data*, *bootstrap_eeg_erp*, *find_sample_p_value*, and *p_value_fdr_correction* function for each subject. The inputs for *analyze_across_subjects* are *first_subject_index*, *last_subject_index*, *data_directory*, and *array_shape*. Both *first_subject_index* and *last_subject_index* are ints which will be used to select the range of subject IDs to be run through the function while *array_shape* is a CxS tuple used to define the number of channels and samples. The outputs are *significant_subject_count*, *erp_times*, *combined_erp_target_median,* *combined_erp_nontarget_median*, *subjects_target_median*, and *subjects_nontarget_median*. Each subject's file will be run, adding the *is_significant_int* array to an array of dimensions CxS called *significant_subject_count* which will contain the number of subjects with a significant p value at each time point. The median values of *eeg_epochs_target* and *eeg_epochs_nontarget* will each be appended to *subjects_target_median* and *subjects_nontarget_median* which are arrays of dimensions NxCxS where N = number of subjects. The median of these two arrays to limit the impact of artifacts will be returned as *combined_erp_target_mean* and *combined_erp_nontarget_mean* with dimensions CxS.

*2.7get_erp_range and ADD FINAL FUNCTION HERE*

In order to find the topology of the specific time ranges belonging to N2 and the P300, *get_erp_range* was used to select only the target time range from one subject of *subjects_target_median* and *subjects_nontarget_median*. The inputs are

**Results**

Using the *plot_significance_across_subjects* function (figure 1), channels with a greater N2 and P3b signal can be identified. For both P3b signal, the channel at index 7 has the greatest number of subjects with a significant difference with two peaks of 3. Regarding the N2 signal, the channel at index 1 has the greatest number of subjects with a significant difference, peaking at 4. Channels at indexes 0, 2, and 5 show the lowest overall significance for the N2 time window, and the channel at index 0 has the lowest number of significant differences in the P3b time window. This figure is important when it comes to determining which channels to use for the P300 Speller.

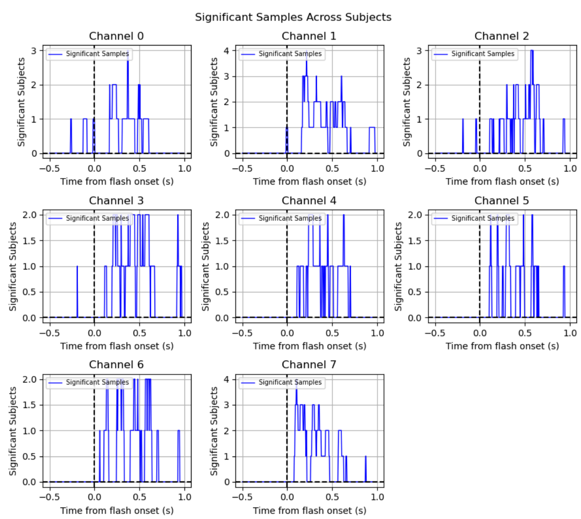


**Figure 1.** *Plot_significance_across_subjects* output. Number of subjects with a significant p value at each time point across channels.

When looking at the plots from individual subjects, some subjects such as subject 3 (figure 2) show a positive deflection around 250-500 ms where the P3b is expected to occur and a negative deflection from approximately 200-300 ms where the N2 is expected to occur. However, other subjects such as subject 8 (figure 3), while still showing a significant difference between target and nontarget ERPs, show the inverse with a positive deflection followed by a negative deflection during the N2 and P3b time windows respectively. Whether or not the N2 and P3b are negative and positive as is standard, significant differences between the target and nontarget ERPs can still be observed in different channels which is necessary for the P300 Speller to be effective.

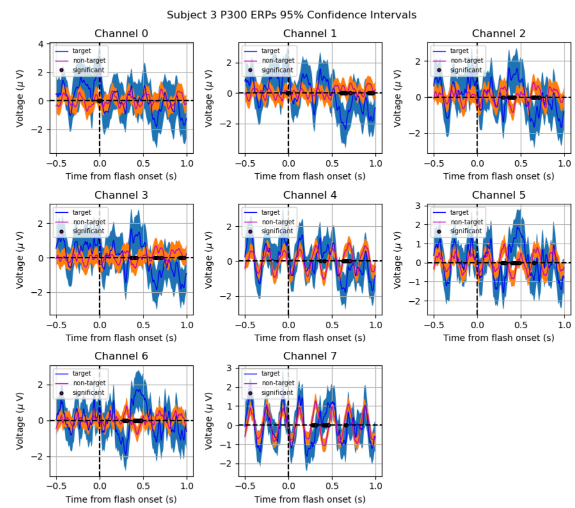


**Figure 2.** Subject 3 Target ERPs (blue) compared to nontarget ERPs (orange) with significance plotted as dots.

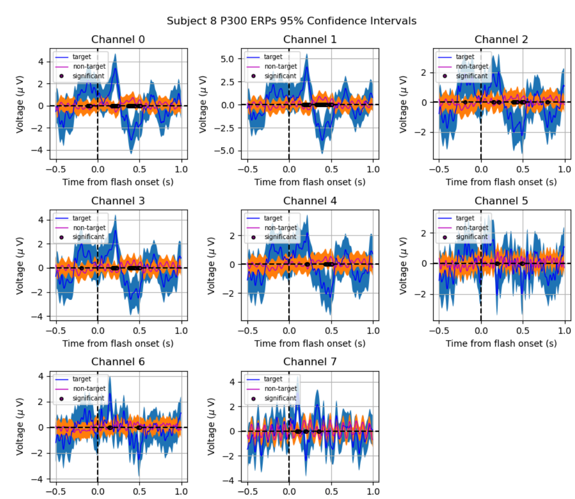


**Figure 3.** Subject 8 Target ERPs (blue) compared to nontarget ERPs (orange) with significance plotted as dots.

Because Guger et al. (2009) does explain which electrode goes with which channel, this information had to be inferred when creating a topology map. The final order from index 0-7 was determined most likely to be P3, Po7, P4, Po8, Oz, Pz, Fz, Cz. The reasoning behind this was that channel 7 showed the greatest overall significance for N2 and P300 in both subjects 3 and 8 while also showing strong overall significance between subjects. Additionally, Guger et al. (2009) reported that the Cz channel had the highest peak voltage at the P300 which matches what was seen in channel 7.

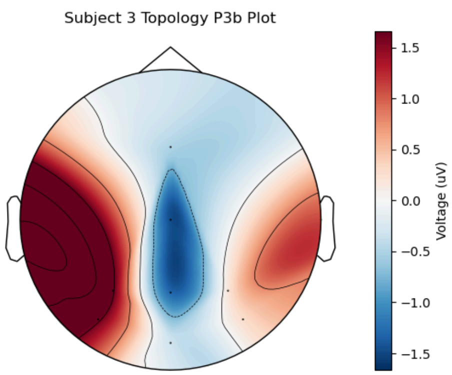


**Figure 4.** Topology plot of subject 3 P3b.

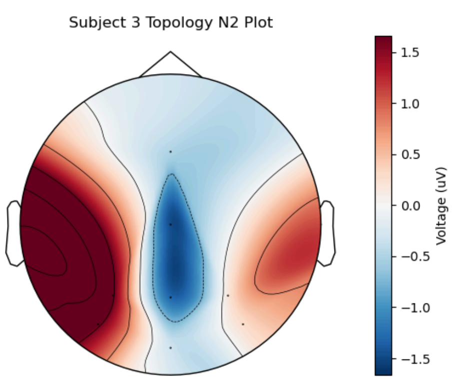


**Figure 5.** Topology plot of subject 3 N2.

When plotting the topology for subject 3 (figure 4), A relatively symmetrical topology can be seen with greater positive signals near the back of the head which contains the occipital lobe. Negative signals can be seen near the frontal lobe as well which can be observed with P300 topology. Additionally, the pattern of P3, Po7, P4, Po8, Oz, Pz, Fz, Cz implies an order of left electrodes, right electrodes, and then central electrodes. If the left and right electrodes are swapped, The topology charts are almost perfectly mirrored (not shown) which further supports the idea that the left and right electrodes are the first four channels. Additionally, some of the lowest significance was seen in the first four channels which is to be expected as the central electrodes are where the strongest P300 signal is expected to be observed (Polich J., 2007) rather than the side electrodes.

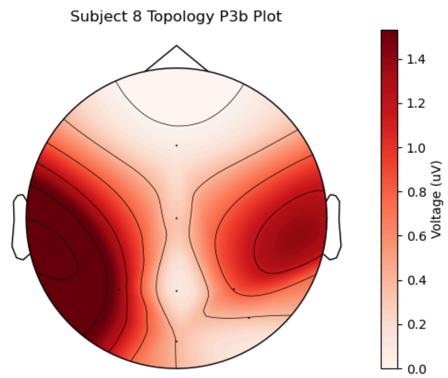


**Figure 6.** Topology plot of subject 8 P3b.

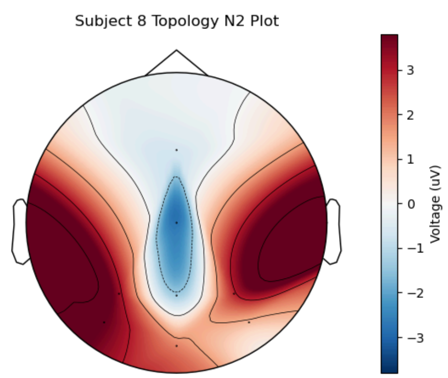


**Figure 7.** Topology plot of subject 8 N2.

The topology for subject 8 (figure 6) is not quite the same, but a similar mirror pattern can be observed for the P3b topology. The N2 topology for both subjects 3 and 8 appear somewhat similar to the P3b, but they have overall more negative signal which is to be expected for the N2 signal. What is seen in these topology maps aligns with the expected results of a P300 Speller. Using this information, should the locations of electrodes not be recorded, these graphs can be used to estimate where they would have been.

**Discussion**

Based on the results from subjects 3 and 8, channels 5, 6, and 7 can be determined to be especially important for determining whether these subjects were observing a flash that contained the target character. For subject 3, strong N2 and P3b signals can be observed in figure 2 with a significant difference from the nontarget signal. Additionally, when paired with the topology graphs, these channels clearly represent the expected strong N2 and P3b signals, meaning they can be used in the P300 Speller.

Though not as apparent from figure 3, these channels can also be used for subject 8. Figure 3 shows a higher range of voltages for channels 6 and 7 which may have caused the lack of significance observed in these channels for subject 8. Additionally, artifacts such as this as well as the negative deflections observed in the P3b range for channels 1-4 for subject 8 make interpreting figure 3 difficult. While artifacts among some of the subjects, especially subject 4, are apparent, determining the cause of these artifacts is impossible. Much is unknown about the specifics behind how Guger et al. (2009) collected the data or any common errors during data collection that may have occurred, the reason for these seemingly inverted N2 and P3b deflections is unknown. While the ERP pattern may be unexpected, significant differences between the target and nontarget data at the expected time points can still be observed which means this data can still be used to determine whether a flash contains the character the user is looking at. However, when looking at the median of subject 8's ERPs rather than the mean, a strong signal is apparent in the central channels Fz, Cz, and Pz, resulting in the topology graph observed in figure 5. Strong signals in the central channels for N2 (Warren, C., Tanaka, J., Holroyd, C., 2011) and P3b (Polich J., 2007) are to be expected .

These figures show that not only should a "one-size-fits-all" P300 Speller program not be created, but the tools to curate a set of channels and time points for each user are within the provided code. Despite showing strong Fz, Cz, and Pz signals for both subjects 3 and 8, subject 8 also has clearly usable signals in channels 0-3 which subject 3 does not have. If one set of channels and time points was chosen for each user, opportunities for those who would be reliant upon the P300 Speller to communicate would be lost. Yes, channels 5-7 could be used for subject 8, but channels 0-4 might be easier to use which could result in faster communication which was reported to be a known issue with P300 Spellers in Guger et al., (2009).

P300 Spellers are useful, but they are not fast to use, so by using the information output by the provided code, channels with the greatest significance for a particular subject can be selected from their training data and later used to determine what characters they are trying to spell. With clean and careful EEG data collection, users could slowly but accurately communicate using only their eyes and the screen in front of them.

**References**

Polich J. Updating P300: an integrative theory of P3a and P3b. Clin Neurophysiol. 2007 Oct;118(10):2128-48. doi: 10.1016/j.clinph.2007.04.019. Epub 2007 Jun 18. PMID: 17573239; PMCID: PMC2715154.

Warren, C., Tanaka, J., Holroyd, C.. What can topology changes in the oddball N2 reveal about underlying processes?. NeuroReport 22(17):p 870-874, December 7, 2011. | DOI: 10.1097/WNR.0b013e32834bbe1f

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