P300-Speller Research Paper

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Introduction

The P300-Speller is part of a group of technology known as a Brain-Computer-Interface (BCI). BCI's are devices that can allow people to more easily interact with the world by bypassing the need for certain parts of their nervous system. The P300-Speller is a device that allows a person to use their brain activity to spell a word on a computer screen. This paper focuses on the RC-paradigm, where each row and column in a 6x6 matrix of characters and numbers is flashed 15 times. The subject types a letter by counting the number of times their target letter flashes within approximately 30 seconds. The brain activity is read in by way of an Electroencephalograph device (EEG) that is temporarily attached to the scalp with electrodes. The code is designed to analyze the information captured by a P300-Speller device to decipher and run calculations on patterns of brain waves from each participant in a P300-Speller experiment. Throughout the application, steps are taken to log the progress of the calculations by saving figures of the processing for visual data analysis as graphs in the output folder. The data collected from these applications helps to visualize the information in a concise and quickly understandable way. These visualizations and significance calculations can be used to guide the design of the P300-Speller's future iterations toward greater accuracy, speeds, and generalizability.

Methods

prepare_epoch_data: Prepares EEG data by splitting it into epochs based on if the epoch contains target or non-target stimuli. The function then calculates the mean event-related potentials (ERPs) for both target and non-targets. This is crucial for getting the data into a state that is able to be used for further analysis and organizing the EEG data into an easier to understand format.

Inputs:
- `subject_number`: Identifies the subject from which the EEG data is collected. Used to load the subject's data for analysis.

Outputs:
- `target_erp`: An array of target ERPs.
- `non_target_erp`: An array of nontarget ERPs.
- `erp_times`: The times at which these ERPs occur.
- `target_epochs`: The epoch data for target events.
- `non_target_epochs`: The epoch data for non-target events.

plot_confidence_intervals: Plots the ERPs for target and non-target events with confidence intervals. Confidence intervals are calculated with the helper function calculate_se_mean which takes either target or non-target epochs as an input and gives the standard error of the mean for the input epoch.

plot_confidence_intervals provides a visual representation of the variability in the ERP data. Aids in visual analysis which is useful for comparing between target and non-target responses.

Inputs:
- `target_erp`: An array of target ERPs.
- `non_target_erp`: An array of nontarget ERPs.
- `erp_times`: The times at which these ERPs occur.
- `target_epochs`: The epoch data for target events.
- `non_target_epochs`: The epoch data for non-target events.

Outputs:
- `None`: (Displays a plot)

bootstrap_p_values: Calculates the p-values for each time point and channel using bootstrapping, provides a statistical measure of the differences between target and non-target ERPs. Essential for identifying statistically significant differences in ERP responses.

Inputs:

- `target_epochs`: The epoch data for target events.
- `non_target_epochs`: The epoch data for non-target events.

Outputs:

- `p_values`: An array of p-values representing the statistical significance of differences at each time point and channel.

<u>plot_confidence _intervals_with_significance:</u> Similar to the function <u>bootstrap_p_values</u> but additionally marks statistically significant differences between target and non-target ERPs. Enhances the visual analysis by highlighting areas of significant difference, making it easier to identify noteworthy patterns in the data.

Inputs:

- `target_erp`: An array of target ERPs.
- `non_target_erp`: An array of nontarget ERPs.
- `erp_times`: The times at which these ERPs occur.
- `target_epochs`: The epoch data for target events.
- `non_target_epochs`: The epoch data for non-target events.
- `p_values`: An array of p-values representing the statistical significance of differences at each time point and channel.

Outputs:

- `None`: (Displays a plot with significance markers)

<u>eval_across_subjects:</u> Performs a cross-subject analysis to evaluate significant EEG responses, compiles the results together to plot on a summary graph of all subjects with the helper function

<u>plot_significcance_across_subjects</u>. Crucial for understanding patterns across multiple subjects, provides insights into generalizable features of the ERP responses.

Inputs:

- `None`: (Works on a predefined range of subjects)

Outputs:

- `None`: (Displays a plot that summarizes the data across subjects)

<u>plot_group_median_erp_spatial_distribution:</u> Calculates and plots the median ERP distribution for significant ERP components (e.g. N2, P3b) across the scalp. Provides a spatial map of the ERP activity. Important for identifying the distribution of ERP response across different Brain regions.

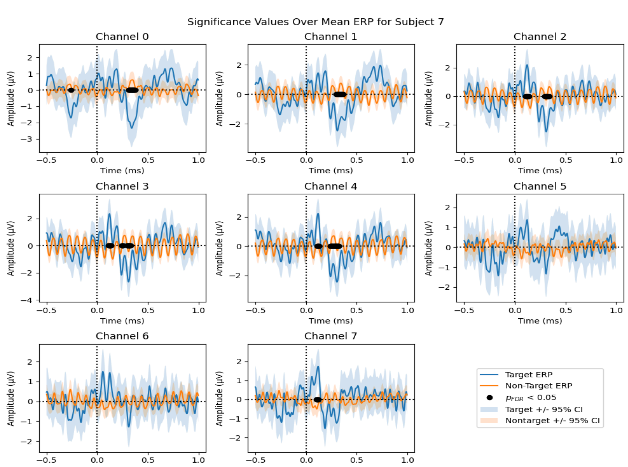
Inputs:

- `None`

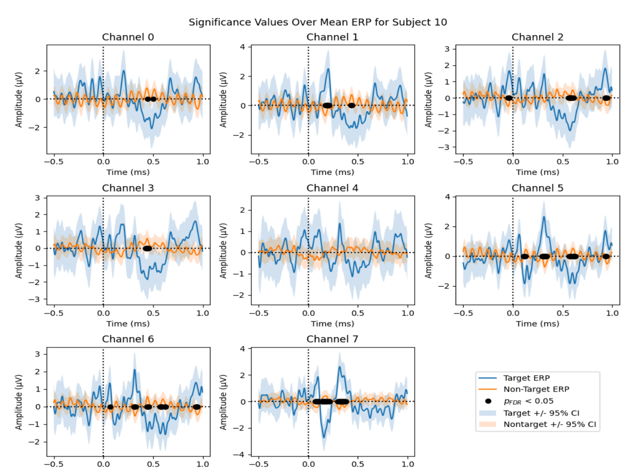
Outputs:

- `None`: (Displays a spatial plot)

Results



(Figure 1) Graph of Subject 7's Mean ERP and Significance



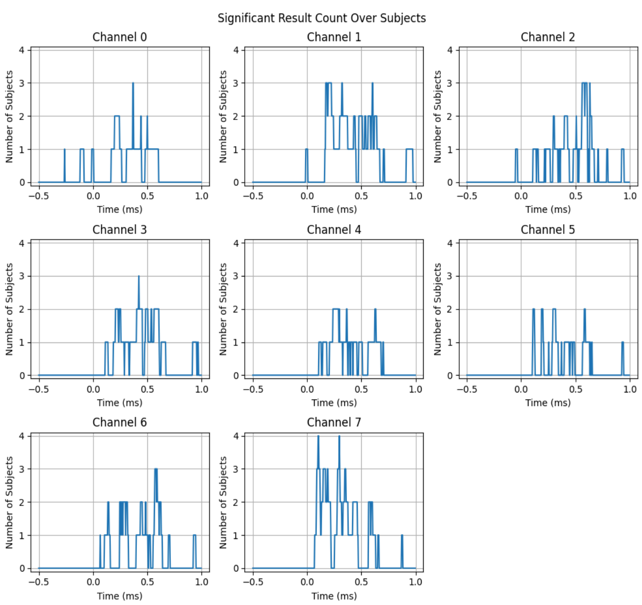
(Figure 2) Graph of Subject 10's Mean ERP and Significance

Explanation: Displays the average voltage readings (ERP mean) for both target and non-target data across every event where a row/column was flashed to subject 7. Also displays p-value in black to denote values that were NOT likely to occur by random chance.

Results: Figure 1 suggests that the fluctuations observed in Channel 0 lack the consistency required for reliable analysis, attributed to notable activity preceding the target event. This pattern likely indicates that Channel 0 corresponds to the frontal lobe, where facial movements or incidental thoughts may influence the recorded data. Additionally, the parietal lobe exhibits significant activity, characterized by expected hyperpolarizations shortly following the target event, underscoring its relevance in the observed responses.

Explanation: Displays the average voltage readings (ERP mean) for both target and non-target data across every event where a row/column was flashed to subject 10. Also displays p-value in black to denote values that did NOT likely occur by random chance.

Results: Figure 2 shows findings similar to Figure 1, emphasizing the importance of the parietal data from channels 1-3. Furthermore, the PO7 sensor data displays a significant use of the P sensors and the Cz sensor in both subjects 7 and 10.



(Figure 3) Significance Graph for All Subjects

Explanation: Expanding upon the initial observations in Figures 1 and 2, this graph presents the frequency of subjects displaying significant p-values in their event-related potentials (ERPs) at successive time points throughout the epoch.

Results: The data revealed in the graph demonstrates that the EEG measurements recorded subsequent to the presentation of a letter are statistically significant. This indicates that the responses are not mere products of chance but are instead authentic, analytically determined reactions to the stimulus event. The graph thus facilitates several determinations regarding the efficacy of specific EEG sensors, highlighting those that yield the most relevant and consistent data. Additionally, it identifies the channels that capture significant activity within the approximately 500 milliseconds following the exposure to the target letter.

Figure 4:

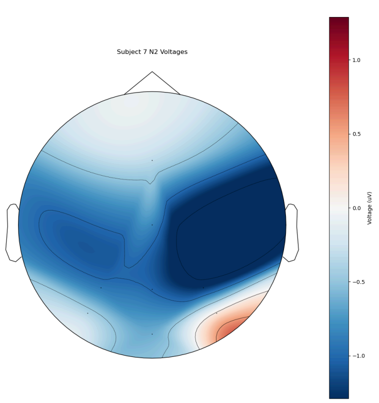
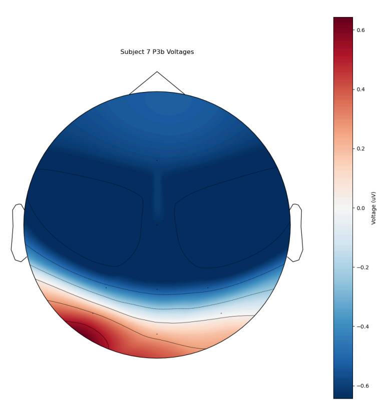


Figure 5:



N2 (Figure 4) and P3b (Figure 5) Median Voltages Spatial Graph: Displays the median voltage for subject 7 of ERPs within the N2 time range (200-300 milliseconds) or the within the P3b time range (300-600 milliseconds).

Results: The above figures offer crucial insights into the brain's response to the target event, highlighting marked activity within the posterior parietal lobe. This observation aligns with established knowledge, given the parietal lobe's integral role in mediating P300 brain wave responses. Such findings validate the efficacy of our channel configuration, confirming accurate detection of anticipated reactions in the parietal region.

Figure 6:

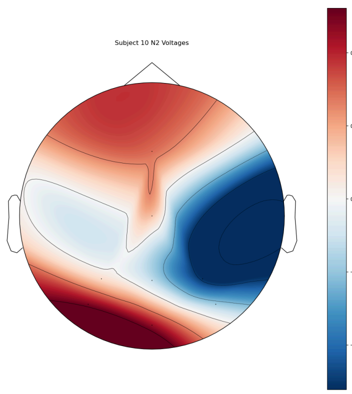
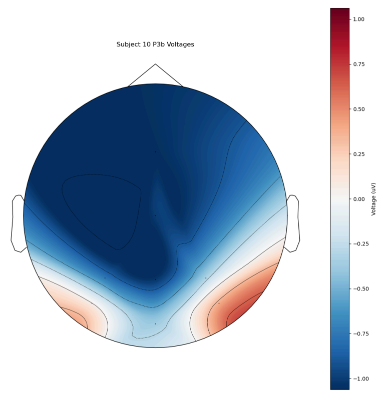


Figure 7:



N2 (Figure 6) and P3b (Figure 7) Median Voltages Spatial Graph: Displays the median voltage for subject 10 of ERPs within the N2 time range (200-300 milliseconds) or the within the P3b time range (300-600 milliseconds).

Figure 8:

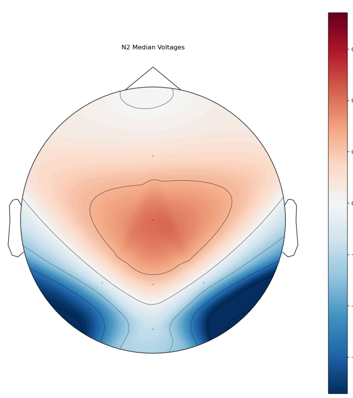
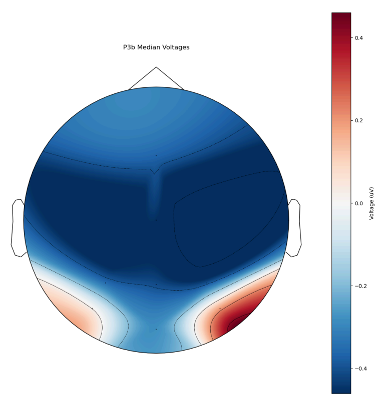


Figure 9:



N2 (Figure 8) and P3b (Figure 9) Group Median Voltages Spatial Graph: These figures provide Median Voltage Spatial Graphs, which illustrate the median voltage of all subject's event-related potentials (ERPs) within the N2 (200-300 milliseconds) and P3b (300-600 milliseconds) timeframes.

Results (Figures 6-9): The topographic maps for the N2 range on subjects 7 and 8 **(Figures 4 and 6)** reveal significant background noise and artifacts, a trend that is observable across all subjects' topographic mappings. These artifacts are most present in the N2 graph, where the frontal lobe changes significantly between subjects. Yet, when examining the median across all subjects **(Figures 8 and 9)**, there is a noticeable decline in these interferences, resulting in a clearer depiction of brain activity. The spatial graph for the median voltage during the N2 time frame indicates heightened activity in the parietal and frontal lobes. During the P3b interval, the spatial graph highlights the parietal-occipital lobes as the predominant sites of activity, with the parietal and frontal lobes also showing notable hyperpolarization. This observation reinforces the rationale behind the configuration of the channels for the spatial mapping, as these lobes are expected to be engaged within these specific temporal windows.

Discussion

In analyzing the effectiveness of the P300-Speller, a Brain-Computer Interface (BCI) device, we have examined the consistency of channels and time points that yield the most reliable EEG readings for interpreting user intent. The data suggests that Channel 0, preliminarily identified as the frontal lobe, exhibits significant pre- and post-stimulus peak action potentials and hyperpolarizations. These findings imply that its readings may be confounded by extraneous factors such as muscle activity or unrelated mental processes, making it less reliable for our purposes. On the other hand, Channels 5 and 7, corresponding to the posterior parietal lobe, showed a marked response following the stimulus flash within the P3b time range of 300-600ms. This concurs with general knowledge of P300s and the literature. This activation is clearly expressed in the peak action potentials shown in Figures 8-9. This indicates its crucial role in the mental recognition processes. This aligns with the established knowledge of occipital lobe function and the sensor layout elaborated in the Guger paper [1].

Furthermore, Channel 1 is the Cz electrode sensor located at the juncture of the frontal and parietal lobes. It demonstrates significant activations, again emphasizing the importance of the electrodes in the central and parietal regions of the brain. The activities observed in Channels 2 through 4, positioned over the anterior and central parietal lobe areas, during the P3b time interval (300-600 milliseconds) are consistent with the parietal lobe's involvement in object recognition tasks. Again, this Cz node's importance concurs with information on page 4 of the Guger paper [1].

Given these observations, we initially created a logical layout of channels, which the dataset curator later corroborated. This confirmation came after we reached out to validate our findings, where they stated: "The order you quote is already the correct one [...]." This verification from the dataset's author endorses our approach and supports our chosen channel arrangements.

Considering the potential for variance in signal quality due to individual anatomical and physiological differences, a one-size-fits-all BCI approach may not be the most effective. Instead, our findings suggest a tailored application, where channels are selected based on a standardized understanding fine-tuned to each subject's unique physiology. The consistent time points across subjects should be retained to ensure consistent detection of signals from the P300 device while allowing for the identification of any abnormal channel data that may necessitate individual adjustment.

Our analysis underlines the need for a semi-individualized approach to BCI channel configuration to achieve optimal P300 function. This strategy is informed by both the generalized brain response patterns and the individual-specific brain mapping confirmed through our research and the subsequent validation from the dataset curator. Using this data, we could develop a BCI product that is marketable and generalizable.

References

[1] C. Guger, S. Daban, E. Sellers, C. Holzner, G. Krausz, R. Carabalona, F. Gramatica, and G. Edlinger, "How many people are able to control a P300-based brain-computer interface (BCI)?," Neurosci. Lett., vol. 462, pp. 94–98, 2009.
[2] Ortner R. (2015) "Visual P300 speller". http://bnci-horizon-2020.eu/database/data-sets
[3] (ChatGPT, Used solely for rephrasing already-written analyses; never used for coming to conclusions or other logical work done in the project, February 21, 2024)