

Electrophysiological Fingerprints of Good Executive Function Across Multiple Tasks Identified Using Interpretable Machine Learning

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Introduction

Executive function is a higher-order cognitive process that supports goal-directed behavior and cognitive control, playing a key role in information maintenance and updating, response inhibition, conflict control, and behavioral regulation. Good executive function reflects the efficient operation of these cognitive control processes. Identifying electrophysiological features associated with good executive function may help clarify the neural mechanisms underlying individual differences in executive function. This study integrated electroencephalography (EEG) data from multiple executive function tasks across multiple datasets, used machine learning algorithms to identify and distinguish key electrophysiological indicators associated with good executive function and its core components, and applied interpretable methods to provide new insights into these indicators.

Methods

EEG data were analyzed from 188 participants across five datasets and four executive function tasks: the N-back task, Stop-signal task, Stroop task, and Switch task. After standardized preprocessing, features were extracted from single epochs for each participant, including multi-band power across all electrodes and functional connectivity within regions of interest. We first compared differences in EEG features at the participant level. Then, for each executive function

task and the general executive function derived from these tasks, four machine learning classifiers (Support Vector Machine, Linear Discriminant Analysis, K-Nearest Neighbors, Random Forest) were used to classify good and poor executive function, multiple metrics were used to compare classification performance. Finally, SHapley Additive exPlanations (SHAP) was applied to interpret model predictions and assess the importance of EEG features.

Results

Overall, in the classification of good and poor executive function across tasks, the SVM and RF models outperformed the LDA and KNN models. SVM showed the best performance, with a mean accuracy of 63.46%, whereas KNN showed the weakest performance, with a mean accuracy of 61.83%. Among the four executive function tasks, the Switch task achieved the highest classification accuracy, with a mean accuracy of 69.33%, whereas the Stroop task showed the lowest classification accuracy, with a mean accuracy of 53.59%, only slightly above chance level. The mean accuracy for general executive function classification was 57.47%. By calculating SHAP values for individual electrophysiological features and ranking feature importance, we highlighted the importance of power features across multiple regions, including the frontal and central regions. In particular, increased frontal-midline Theta power contributed to classification toward better executive function.

Conclusions

This study shows that, by integrating multiple datasets and multiple executive function tasks, EEG features can provide valuable electrophysiological information for distinguishing good executive function and offer cross-task evidence for executive function research. Power features across different frequency bands and brain regions may reflect the neural basis of individual differences in executive function, with frontal-midline Theta activity potentially serving as an important indicator of good executive function. Overall, this study supports the application of machine learning and interpretable analysis methods in the field of executive function, providing new insights into the identification of EEG markers related to executive function, the understanding of its neural mechanisms, and executive function assessment.