

Analysis of Cognitive Load using EEG: Methodological Challenges and Validation

Rith Rajak
24116085

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Abstract

This report details the preprocessing and spectral analysis of EEG data recorded during a mental arithmetic task compared to a baseline resting state. The raw data exhibited significant ocular and low-frequency contamination, necessitating a robust preprocessing pipeline. We explored multiple artifact removal strategies, including Signal Space Projection (SSP) and automated Independent Component Analysis (ICA), both of which proved insufficient for this specific dataset. The final validated approach employed a heuristic "Aggressive ICA" strategy (manually rejecting components 0 and 1). Post-cleaning analysis revealed a distinct increase in Theta band power (4-8 Hz) and a shift in the Theta/Alpha ratio, consistent with high working memory load.

1 Introduction

Electroencephalography (EEG) provides a direct measure of neuronal activity, making it a valuable tool for assessing cognitive states. This project differentiates between a "Baseline" (Rest) state and a "Mental Arithmetic" (Cognitive Load) state using the *Subject00* dataset. The primary objective is to extract reliable cognitive metrics, specifically the Event-Related Synchronization (ERS) in the Theta band.

2 Dataset and Diagnosis

The dataset consists of 19-channel EEG recordings (Standard 10-20 montage). Initial spectral diagnosis revealed severe contamination in the Task condition. The Mental Arithmetic signal exhibited a massive power surge in the Delta band (< 4 Hz) compared to the Baseline. This was identified as characteristic ocular artifacts (blinks and saccades) rather than neural activity.

3 Methodological Iteration: Approaches that Failed

Before arriving at the final solution, several standard preprocessing approaches were tested and rejected based on performance metrics.

3.1 Attempt 1: Signal Space Projection (SSP)

Our initial attempt utilized Signal Space Projection (SSP) to project out artifact vectors.

- **Hypothesis:** Since the artifacts were largely frontal, defining a projection vector based on the Fp1 channel would suppress the noise.
- **Outcome (Failure):** While SSP reduced the amplitude of some blinks, it failed to fully eliminate the non-stationary "drift" in the Delta band. Furthermore, SSP applies a spatial filter that risks distorting the topography of the underlying Theta brainwaves, which are critical for our cognitive load analysis.

3.2 Attempt 2: Automated ICA (Correlation-Based)

We subsequently moved to Independent Component Analysis (ICA) using the *FastICA* algorithm. We attempted an automated cleaning pipeline using correlation thresholds.

- **Method:** We used the Fp1 channel as a proxy for an Electrooculogram (EOG) channel, as no dedicated EOG was available. We instructed the algorithm to find components that correlated with Fp1 signal spikes.
- **Outcome (Failure):** The algorithm returned zero candidates for removal. The statistical threshold for "blink similarity" was not met because the brain signal in Fp1 (Pre-Frontal Cortex activity) was mixed too heavily with the blink artifact. The result was a "cleaned" dataset that was identical to the raw, noisy data.

3.3 Attempt 3: Statistical Variance ICA (Max-Peak Detection)

To overcome the correlation failure, we attempted a statistical approach: calculating the Peak-to-Peak (PTP) amplitude variance of every independent component and automatically rejecting the one with the highest variance.

- **Hypothesis:** Blinks are orders of magnitude larger than brain signals; therefore, the "loudest" component must be the blink.
- **Outcome (Failure):** The algorithm identified Component 11 (ICA011) as the maximum variance source. However, spectral validation showed that removing ICA011 did not reduce the 0–4 Hz Delta spike. The algorithm had likely locked onto a different artifact (e.g., electrode pop or muscle tension) rather than the repetitive ocular activity.

4 Final Methodology: Aggressive Heuristic ICA

To resolve the failures described above, we implemented a robust, manual heuristic approach.

4.1 Preprocessing Steps

1. **Channel Cleaning:** Explicit removal of non-EEG channels ('ECG', 'A2') to prevent topographic mapping errors.
2. **Filtering:** A 1.0 Hz High-Pass filter was applied (FIR design) to remove DC drift and stabilize the baseline for ICA.
3. **Heuristic Component Rejection:** Instead of relying on automated detection, we manually forced the removal of the first two components (**ICA000** and **ICA001**).

4.2 Validation

In ICA, components are sorted by explained variance. Ocular artifacts, being the strongest signals in the recording, almost invariably occupy the first two slots.

- **ICA000:** Topography revealed strong frontal distribution (Blinks).
- **ICA001:** Topography revealed frontal-occipital dipole (Saccades/Head Movement).

Removal of these specific components successfully collapsed the artifact power in the Delta band while preserving the Alpha/Theta peaks required for analysis.

5 Key Findings

With the clean data, we calculated band powers to quantify the cognitive load.

5.1 Band Power Analysis

Metric	Baseline	Mental Arithmetic	% Change
Theta/Alpha Ratio	0.321	0.534	+66.3%
Frontal Asymmetry (FAA)	–	0.33	(Left Dominance)

Table 1: Summary of Cognitive Metrics. The sharp increase in the Theta/Alpha ratio indicates high working memory demand.

- **Theta ERS:** We observed a significant Event-Related Synchronization (increase in power) in the 4–8 Hz band.
- **Frontal Asymmetry:** The positive FAA score (0.33) indicates greater relative activity in the left hemisphere, which is associated with logical and analytical processing tasks.

6 Conclusion

This study successfully isolated neural activity from a highly contaminated EEG recording. By systematically testing and rejecting automated methods (SSP, Auto-ICA) in favor of a heuristic removal of the top two variance components, we revealed a clear cognitive signature. The results confirm a significant elevation in the Theta/Alpha ratio (0.534), validating the subject's engagement in high-load mental arithmetic.