EEG Signal Analysis Across Multiple Cognitive Paradigms

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Abstract

This report presents a comprehensive analysis of multichannel EEG data recorded during four cognitive paradigms: the oddball task, Stroop task, task-switching paradigm, and dual-task paradigm. A structured signal processing pipeline involving bandpass filtering, event-based epoching, condition-wise averaging, and group-level statistical analysis was implemented using Python and the MNE toolbox. Different frequency bands were examined based on the cognitive demands of each task, including alpha (8–13 Hz), theta (4–8 Hz), beta (13–30 Hz), and gamma (30–50 Hz). The results demonstrate task-specific modulation of EEG rhythms, highlighting how different neural oscillations reflect distinct cognitive processes such as attention, conflict monitoring, task switching, and sustained workload. Group-level paired statistical analysis was used to identify consistent neural patterns across subjects, overcoming high inter-subject variability observed at the single-subject level.

Observations from the Oddball Paradigm

The oddball paradigm involves detecting rare target stimuli embedded within frequent non-target stimuli. Initial alpha-band (8–13 Hz) analysis showed minimal visual differences between target and non-target conditions for most subjects. This suggests that alpha oscillations, which are often associated with cortical idling or inhibition, are not strongly modulated by simple stimulus detection in this dataset.

In contrast, gamma-band (30–50 Hz) analysis revealed clearer differentiation between target and non-target conditions. Gamma activity showed stronger spatial contrast, particularly during target trials, indicating increased local cortical processing and stimulus evaluation. Group-level averaging and paired statistical testing confirmed that gamma-band activity is more sensitive to the attentional demands of the oddball task. This aligns with the known role of gamma oscillations in perceptual binding and stimulus-driven processing.

Overall, the oddball results demonstrate that higher-frequency activity is more informative than alpha-band activity for detecting neural responses associated with rare stimulus detection.

Observations from the Stroop Task

The Stroop task introduces cognitive conflict by presenting incongruent stimuli that require suppression of automatic responses. Alpha-band analysis across subjects showed limited and inconsistent differences between congruent and incongruent trials. Only a small number of subjects exhibited visible alpha modulation, suggesting that alpha suppression effects are weak and highly subject-dependent in this paradigm.

Theta-band (4–8 Hz) analysis produced much clearer results. Incongruent trials consistently elicited stronger theta activity compared to congruent trials, particularly over frontal and fronto-central regions. Group-level grand averages and paired t-tests confirmed statistically significant theta increases during incongruent conditions. This reflects enhanced conflict monitoring and executive control, processes that are strongly associated with frontal theta oscillations.

These observations indicate that theta-band activity is a robust neural marker of cognitive conflict in the Stroop task, whereas alpha-band effects are comparatively subtle.

Observations from the Task-Switching Paradigm

The task-switching paradigm requires subjects to alternate between different task rules, imposing demands on cognitive flexibility and task-set reconfiguration. Single-subject theta-band analyses showed substantial variability, with some subjects exhibiting strong differences between switch (target) and repeat (non-target) trials, while others showed minimal effects.

Despite this variability, group-level theta-band analysis revealed consistent increases in theta power during task-switching trials. Statistical maps demonstrated significant frontal theta modulation, indicating engagement of executive control mechanisms responsible for updating task rules. These findings are consistent with theoretical models that link theta oscillations to cognitive control and mental flexibility.

The task-switching results further reinforce the importance of group-level analysis in EEG studies, as meaningful cognitive effects may only emerge when inter-subject variability is averaged out.

Observations from the Dual-Task Paradigm

The dual-task paradigm imposes sustained cognitive workload by requiring simultaneous processing of multiple task streams. Beta-band (13–30 Hz) activity was analyzed as it is closely associated with sustained attention, task maintenance, and motor planning.

Single-subject beta maps showed modest but systematic differences between target and non-target conditions. Group-level analysis revealed clearer patterns, with beta activity consistently higher during target trials, indicating increased cognitive workload. This confirms the role of beta oscillations in maintaining active task engagement over extended periods.

Further separation of dual-task conditions into visual and auditory targets demonstrated modality-specific beta modulation. Visual targets and auditory targets showed distinct spatial distributions, suggesting that the brain dynamically allocates attentional resources depending on sensory modality while maintaining overall task engagement. Paired statistical tests confirmed that both visual and auditory targets elicited significantly higher beta activity than their corresponding non-target conditions.

These findings highlight beta oscillations as reliable markers of sustained workload and multimodal attention in dual-task scenarios.

Cross-Paradigm Interpretation

Across all paradigms, a clear pattern emerges linking specific EEG frequency bands to distinct cognitive processes. Gamma activity was most sensitive to stimulus detection in the oddball task, theta activity robustly reflected conflict monitoring and task switching, and beta activity indexed sustained cognitive workload during dual-task performance.

Alpha-band effects were comparatively weak and inconsistent across paradigms.

The results collectively demonstrate that appropriate selection of frequency bands based on task demands is critical for meaningful EEG interpretation. Furthermore, group-level paired statistical analysis proved essential for revealing consistent neural patterns that were often obscured at the single-subject level.

Cell-wise Observations and Interpretation

Cell 6: Alpha-band Analysis in the Oddball Paradigm

This cell extracts alpha-band (8–13 Hz) EEG activity and aligns it with target and non-target stimuli in the oddball task. The continuous EEG signal is segmented into stimulus-locked epochs, averaged across trials, and visualized using scalp topographic maps. This processing pipeline allows examination of how alpha-band activity is spatially distributed across the scalp during different stimulus conditions.

An important observation from this cell is that alpha-band target-specific effects are highly time-localized. Since alpha activity often reflects global inhibitory or attentional states rather than brief stimulus-locked responses, averaging across the entire epoch can reduce visible differences between target and non-target conditions. As a result, alpha-band contrasts in the oddball task appear weak, even though subtle temporal modulations may still be present immediately following stimulus onset.

Cell 8: Frequency-Domain Analysis Using FFT in the Oddball Task

This cell analyzes EEG data in the frequency domain using the Fast Fourier Transform (FFT) to identify dominant frequency components present during the oddball task. Unlike event-related analyses, this approach provides a global overview of spectral content across the entire recording.

The key observation is that this analysis does not distinguish between target and non-target conditions because FFT is applied to the continuous signal rather than to stimulus-locked epochs. As a result, task-specific effects are averaged out. To directly compare target versus non-target responses in the frequency domain, FFT should be applied separately to epochs corresponding to each condition. This cell therefore serves as an exploratory spectral analysis rather than a condition-specific comparison.

Cell 9: Notch Filtering and Frequency-Domain Noise Removal

This cell applies a notch filter to remove narrowband electrical interference, followed by FFT-based frequency analysis. EEG recordings are commonly contaminated by power-line noise at 50 Hz (and its harmonics), which can dominate the frequency spectrum and obscure neural signals.

The notch filter effectively suppresses this narrowband interference without affecting nearby neural frequencies. The resulting FFT plots demonstrate a cleaner spectral representation of EEG activity, confirming that the observed power-line components are non-neural artifacts. This step is critical for ensuring that subsequent gamma-band and beta-band analyses are not distorted by electrical noise.

Cell 10: Gamma-band Analysis in the Oddball Paradigm

This cell extracts gamma-band (30–50 Hz) EEG activity, removes power-line noise, aligns the signal to target and non-target stimuli, and visualizes spatial differences using scalp topographic maps. Gamma oscillations are closely associated with active cortical processing, stimulus evaluation, and perceptual integration.

A key observation is that gamma-band activity shows a much stronger contrast between target and non-target conditions compared to alpha-band activity. This indicates that target detection in the oddball task primarily engages active cortical processing rather than global inhibitory mechanisms. The enhanced gamma response reflects increased neural firing and information processing required to detect and evaluate rare target stimuli.

Cell 11: Butterworth-Based Gamma-band Filtering

This cell refines gamma-band extraction using a Butterworth bandpass filter. The filter removes power-line noise correctly, employs zero-phase filtering to preserve temporal alignment, and avoids unnecessary FFT operations. By using zero-phase filtering, the timing of stimulus-locked neural responses remains intact.

This approach cleanly isolates gamma-band activity and ensures accurate alignment of EEG data with oddball events. Compared to frequency-domain filtering, this time-domain filtering strategy is computationally efficient and well-suited for event-related analyses.

Cell 12: Group-level Gamma-band Statistics for the Oddball Task

This cell performs a complete group-level gamma-band analysis. Gamma-band EEG (30–50 Hz) is extracted for each subject, target and non-target responses are separated, and responses are averaged within each subject. These averages are then combined across all 24 subjects to compute grand averages.

A paired t-test is used to statistically compare target and non-target conditions because both responses come from the same subjects. This within-subject comparison controls for inter-subject variability and isolates task-related effects. The resulting statistical scalp maps show where gamma activity differs significantly, confirming that target detection in the oddball task elicits consistent gamma-band enhancement across participants.

Cell 13: Alpha-band Analysis of the Stroop Task

This cell analyzes alpha-band EEG activity during the Stroop task by separating congruent and incongruent trials and visualizing scalp topographies. Alpha oscillations are often linked to attentional suppression and cortical idling.

The key observation is that alpha-band effects are highly subject-dependent. Strong contrasts between congruent and incongruent conditions are visible only in a subset of participants, particularly Subject 2 and Subject 5. This variability suggests that alpha modulation during the Stroop task is influenced by individual cognitive strategies and baseline attentional states rather than being a robust group-level marker of conflict processing.

Cell 14: Theta-band Analysis of the Stroop Task

This cell focuses on theta-band (4–8 Hz) EEG activity during the Stroop task to study cognitive control and conflict monitoring. Theta oscillations are strongly associated with executive control processes, especially in frontal brain regions.

While most participants exhibit subtle theta-band differences, Subject 6 shows pronounced modulation between congruent and incongruent trials. This highlights significant inter-subject variability in cognitive control engagement. Despite this variability, theta remains a theoretically meaningful frequency band for studying Stroop-related conflict processing.

Cell 15: Group-level Alpha-band Statistics in the Stroop Task

This cell extends alpha-band Stroop analysis to the group level. Alpha activity is extracted for each subject, separated into congruent and incongruent conditions, averaged within subjects, and combined across participants. A paired statistical test is then applied.

Although alpha-band effects are weak at the single-subject level, group-level analysis reveals significant frontal modulation. This suggests that subtle alpha changes related to attentional control become detectable only after averaging across subjects.

Cell 16: Theta-band Analysis in the Task-Switching Paradigm

This cell analyzes theta-band EEG activity during task switching. Task-switching requires updating task rules and reconfiguring cognitive sets, processes strongly associated with theta oscillations.

Theta-band activity increases during switch trials, reflecting enhanced executive control and mental flexibility required to change task rules.

Cell 17: Group-level Theta-band Statistics for Task Switching

This cell performs a group-level theta-band comparison between task-switching (target) and non-switching (non-target) trials using paired statistics. The results demonstrate consistent theta enhancement during task switching across subjects, confirming theta oscillations as a robust marker of cognitive flexibility.

Cell 19: Beta-band Modulation in Dual-task Performance

This cell reveals beta-band modulation associated with increased cognitive workload during dual-task performance. Beta oscillations are linked to sustained attention and active task maintenance, making them suitable for studying dual-task demands.

Cell 20: Modality-specific Beta-band Analysis in Dual-task Paradigm

This cell separates beta-band EEG activity into visual and auditory targets and non-targets. By analyzing these conditions separately, the code visualizes how brain activity differs depending on stimulus modality during dual-task performance.

Cell 21: Group-level Beta-band Statistics for Dual-task Targets

Paired statistical analysis confirms that beta activity reliably increases during dual-task target conditions across subjects. This reflects continuous attention and sustained task maintenance required when managing multiple task streams.

Cell 22: Visual vs Auditory Beta-band Group Comparisons

This final cell performs group-level paired statistical analysis telltales that both visual and auditory targets elicit stronger beta-band activity than non-targets. These findings demonstrate selective and sustained attentional engagement and show that the brain dynamically allocates resources across modalities during dual-task performance.

Conclusion

This report presented a unified interpretation of EEG analyses conducted across multiple cognitive paradigms using frequency-specific signal processing techniques. By systematically examining alpha, theta, beta, and gamma bands, the study demonstrated how different neural oscillations correspond to distinct cognitive operations such as attention, conflict resolution, cognitive flexibility, and sustained workload.

The findings emphasize the necessity of group-level analysis in EEG research due to high inter-subject variability. When analyzed collectively, consistent and theoretically meaningful neural patterns emerged across all paradigms. Overall, this work illustrates how structured EEG signal processing and statistical analysis can transform noisy electrophysiological recordings into interpretable markers of human cognition.