Frontal EEG Dynamics in an ADHD Participant across Baseline, Medication, and Meditation

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***Abstract*—This study investigates how frontal brain activity changes across baseline, medication, and meditation conditions in an individual with ADHD, using daily EEG recordings over a structured multi-day protocol. By focusing exclusively on frontal electrode sites, the study reflects real-world constraints while exploring the reliability and sensitivity of EEG for monitoring intervention effects. Sessions included a mix of resting and cognitive tasks, repeated consistently across conditions. The analysis revealed stable spectral patterns during resting states, with more dynamic variations during tasks. In particular, stimulant medication increased frontal theta activity and reduced beta power, an unexpected shift from conventional ADHD treatment signatures, while meditation led to a reduced theta-beta ratio and increased beta power, especially in frontopolar regions. These results highlight the nuanced effects of each intervention and underscore the feasibility of using low-channel frontal EEG for individualized longitudinal monitoring. The study also offers a transparent and replicable preprocessing pipeline, designed to ensure artifact robustness and spectral reliability, which may inform future work in neurophysiology, BCI, and digital mental health tracking.**

I. Introduction

Electroencephalography (EEG) provides a window into the brain's dynamic rhythms and has long been used to study neurodevelopmental conditions such as attention-deficit/hyperactivity disorder (ADHD). Individuals with ADHD often display elevated power in lower-frequency bands (especially theta) and reduced activity in higher-frequency bands like beta, leading to an increased theta/beta ratio (TBR). This TBR metric has been proposed as a potential biomarker of cortical underarousal, particularly in children with ADHD. Early studies, such as [1], observed that stimulant medication could normalize this imbalance by reducing theta and increasing beta activity. However, more recent work has questioned the consistency and generalizability of TBR, particularly in adults, highlighting significant heterogeneity in EEG profiles and subtypes between individuals [2].

Beyond pharmacological treatment, behavioral and contemplative interventions such as meditation have shown promise in modulating EEG activity. For example, open-monitoring (OM) meditation practices have been associated with increased alpha and frontal theta activity, potentially reflecting an attentive yet relaxed mental state [3], [4]. These contrasting interventions—stimulant medication versus meditation—affect neural dynamics through fundamentally different mechanisms, and comparing their electrophysiological effects within the same individual may offer new insights into ADHD-related dysregulation.

Despite advances in EEG research, most studies on ADHD and interventions remain limited by sparse temporal sampling, often relying on a single pre/post measurement or wide gaps between sessions. This makes it difficult to disentangle true intervention effects from natural variability in brain states. A recent paradigm shift has been introduced by dense, single-subject longitudinal designs [5], where EEG is recorded daily across extended periods. These high-frequency designs capture both stable neural traits and state-dependent fluctuations, revealing that even "outlier" days may belong to coherent alternate clusters of brain activity. Such approaches emphasize the importance of tracking brain dynamics over time rather than relying on static baselines.

In this study, we adopt a similar dense, within-subject design to examine how frontal EEG activity in an adult with ADHD changes under three conditions: baseline (no intervention), after taking Vyvanse (a commonly prescribed stimulant), and after engaging in OM chanting meditation. Each of the 21 sessions follows an identical task protocol, alternating between eyes-closed (EC) and eyes-open (EO) states. Due to practical constraints, including the difficulty placing posterior electrodes, we focus exclusively on four frontal channels (Fp1, Fp2, F7, F8), which are particularly relevant for arousal, attention, and executive function. This minimalist montage also reflects real-world limitations often encountered in home-based or consumer EEG studies.

To maximize signal reliability, we implement a rigorous preprocessing pipeline, including artifact correction using ICA (with a regression fallback), common-average rereferencing, and automated epoch selection. We then compute spectral power across canonical EEG bands (delta, theta, alpha, beta, and low gamma), track the theta/beta ratio, and assess frontal asymmetry. In addition to hypothesis-driven analyses, we explore session-to-session spectral similarity and latent clustering, based on Chuang's approach, to better understand the temporal dynamics of brain state transitions.

Our objectives are twofold: (1) to assess how frontal EEG activity changes across pharmacological and meditative interventions, using repeated, real-world measurements; and (2) to demonstrate how artifact-aware processing and high-frequency sampling can enable stable, interpretable EEG analysis, even with minimal hardware. By combining dense temporal sampling with transparent methodology, this work contributes both empirical findings and methodological tools for longitudinal EEG research in ADHD and beyond.

II. Methodology

A. Tools and Experimental Setup

This study used the OpenBCI Ganglion board, a compact 4-channel EEG system capable of recording at 200 Hz sampling frequency. Data acquisition was conducted using OpenBCI GUI and saved in CSV format with synchronized timestamps. The subject used gel-based Ag/AgCl electrodes placed at Fp1, Fp2, F7, and F8, following the international 10–20 system for frontal electrode positioning. This setup was selected due to practical constraints (e.g., difficulty placing occipital electrodes due to hair volume) and to maintain focus on the prefrontal and lateral frontal areas, which are particularly relevant in ADHD and meditation research.

Signal processing and analysis were implemented in Python, using the following packages: `numpy`, `scipy`, `pandas`, `scikit-learn`, `matplotlib`, and `seaborn`, along with custom scripts for artifact rejection, power spectral analysis, epoch selection, and reporting.

The source code and dataset used in this study are publicly available.[1]

B. Data Collection Protocol

Recordings were conducted by a single adult subject with a clinical diagnosis of ADHD over twenty-one sessions partitioned evenly into three experimental conditions. Seven sessions were completed at baseline without intervention, seven sessions were recorded following stimulant administration (Vyvanse), and seven sessions were recorded following a 15-minute OM chanting meditation.

Each session included six 30-second tasks in fixed order: (1) *Rest* (eyes closed), (2) *Math* (eyes open), (3) *Music* (eyes closed), (4) *Video* (eyes open), (5) *Memory retrieval* (eyes closed), (6) *Color counting* (eyes open, 120s recorded, first 30s used). Sessions were performed in a consistent in-home environment.

C. Data Preprocessing

1) Conversion and Scaling:: Raw signal values were rescaled using OpenBCI's published scaling factor (0.001869917138805) to convert ADC counts to microvolts (μV). Signals were then zero-centered per channel.

2) Filtering:: Signals were filtered with a notch filter at mains frequency and a 1–40 Hz band-pass (4th-order Butterworth, zero-phase). High-pass filtering at 1 Hz suppressed drift and sweat artifacts while preserving band power.

3) Artifact Removal: ICA + Regression Fallback: An ICA-first, regression-second strategy was employed. FastICA was applied to z-scored data, and independent components were scored using a set of objective criteria: correlation with an EOG proxy, low-frequency dominance in the 0.5–3 Hz range, kurtosis, and frontal loading inferred from the mixing matrix. Components meeting stringent blink or spike criteria were removed with an explicit guardrail to preserve alpha-band activity. When ICA did not converge or when no components met removal criteria, a regression fallback was used in which the frontopolar mean, computed as (Fp1 + Fp2)/2, was subtracted from the lateral channels F7 and F8 to reduce residual ocular contamination.

4) Rereferencing:: Common average referencing (CAR) was applied across the four channels post-artifact correction.

5) Epoch Selection:: A clean 15s sub-epoch was selected from each task by excluding segments containing spikes above ± 50 μV. This ensured artifact-free PSD estimation.

D. Power Spectral Analysis

Power spectral density was computed on each cleaned epoch using Welch's method with 2 s Hann windows and 50% overlap. Median averaging across segments reduced the influence of residual transients, and spectra were evaluated from 0.5 to 40 Hz using 80 frequency bins.

E. Feature Extraction

From each PSD, band-limited powers were extracted for delta (0.5–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–30 Hz), and low gamma (30–40 Hz). The theta/beta ratio was computed as a summary arousal index, and frontal asymmetry was quantified using the Frontal Asymmetry Index

$$FAI = \frac{P_{\text{right}} - P_{\text{left}}}{P_{\text{right}} + P_{\text{left}}}.$$

The FAI was evaluated for both the F8–F7 and Fp2–Fp1 pairs within each band.

F. Statistical and Temporal Analysis

We compared Baseline vs. Medication (H1) and Baseline vs. Meditation (H2), with a focus on eyes-closed tasks. For each session, condition, and task, PSD metrics were aggregated. Intra-condition PSD similarity was assessed using Pearson correlation. Tasks were also grouped into *resting* (EC: Rest, Music, Retrieval) and *non-resting* (EO: Math, Video, Color Counting) conditions.

Additional exploratory analysis included clustering daily PSD vectors to identify alternate spectral states, inspired by the longitudinal EEG clustering work in [5].

III. Results

A. Inter-session Similarity Analysis

To assess the stability and repeatability of EEG responses across sessions, we computed inter-session similarity for each task across the three experimental conditions. Specifically, we calculated the Pearson correlation between the power spectral density (PSD) profiles across the 7 recording days for each task within each condition (Baseline, Medication, Meditation). This resulted in a 7×7 correlation matrix per (task, condition) pair, reflecting how similar the spectral content was across sessions.

Figure 1 presents a composite visualization of all 18 correlation matrices—six cognitive tasks per condition, arranged as 3×2 blocks for each condition (Baseline, Medication, Meditation). Visual inspection indicates three recurring patterns. Under baseline, resting-state tasks such as Rest, Music,

[1] https://github.com/CalBlitz/ADHD-EEG-Study

and Retrieval exhibit consistently high between-day similarity, with many off-diagonal coefficients exceeding $r > 0.8$, consistent with stable endogenous dynamics in the absence of intervention. Under medication, between-day similarity is reduced for several tasks, most notably Math and Video, suggesting greater lability in cortical state or variability in task engagement when pharmacological modulation is present. Under meditation, the picture is mixed: Rest and Retrieval often retain high stability, whereas Music and Math show greater fluctuation across days, a pattern that may reflect non-stationary depth of practice or variable internalization during OM. While these observations are qualitative, they motivate formal statistical comparisons of correlation distributions across conditions and task categories in subsequent analyses.

One caveat is that while visual interpretation suggests patterns, these are not yet statistically confirmed across all matrices. Some apparent differences might arise from transient artifacts or daily state fluctuations. Nonetheless, this qualitative inspection serves as a foundation for deeper time-resolved and network-level analyses.

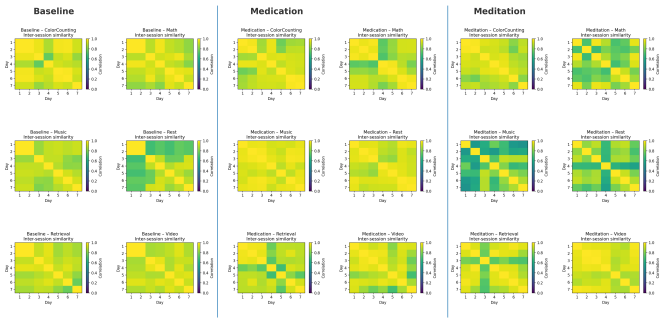

Fig. 1. Inter-session similarity of spectral profiles across 7 recording days for each task (rows) and condition (columns). Each subpanel shows a 7×7 Pearson correlation matrix of PSDs between days for a given task. Diagonals reflect self-similarity (perfect correlation).

B. Spectral Profiles Across Tasks

Figure 2 presents the power spectral density (PSD) overlays for each of the six tasks, where we analyzed median power spectral density (PSD; $\mu V^2/Hz$) across seven recording days per condition at the lateral frontal montage (F7/F8 mean). Plots are shown on a logarithmic ordinate with conventional band demarcations at 0.5, 4, 8, 12, 30, and 40 Hz. Eyes-open tasks (Color Counting, Math, Video) are expected to suppress alpha power relative to eyes-closed tasks (Rest, Music, Retrieval). Because the gamma range is low amplitude in four-channel recordings and susceptible to muscle contamination, interpretations above 30 Hz are conservative.

Color Counting (eyes open) exhibited a dominant delta peak near 2–3 Hz (baseline on the order of 10–30 $\mu V^2/Hz$), followed by a monotonic fall-off through theta–alpha. Alpha power was low, consistent with visual engagement. Relative to baseline, medication reduced low-frequency power from delta through low theta and produced a slight elevation in the 18–26 Hz beta region; meditation produced a milder version of the same pattern, with theta marginally lower than baseline and beta comparable or modestly higher. These changes are consistent with a shift toward a more activated frontal state under externally focused attention.

Math (eyes open) showed the strongest alpha attenuation of the three EO tasks, with a pronounced low-frequency complex in delta–low-theta during baseline and medication sessions. Medication elevated beta modestly relative to baseline, whereas meditation tended to reduce both theta and beta simultaneously, yielding an overall flatter mid-frequency profile. The combination of low alpha and slightly higher beta under medication aligns with increased task engagement; the meditation profile suggests reduced effort or a calmer strategy with fewer high-frequency components.

Video (eyes open) replicated the EO signature with low alpha across all conditions. Medication produced the clearest beta enhancement among the EO tasks, particularly around 20–26 Hz, while marginally suppressing theta. Meditation tracked this pattern more weakly, with small reductions in theta and small increases in low beta. Together the EO tasks indicate that stimulant effects on beta are present when exogenous sensory drive is high, whereas meditation effects are subtler and more variable.

Rest (eyes closed) revealed classical EC structure with sizeable alpha during baseline and a large delta complex near 2–3 Hz. Under medication the spectrum shifted toward higher delta and theta with a concomitant attenuation of alpha and little evidence of beta enhancement; meditation reduced low-frequency power relative to medication and produced a slightly more balanced mid-frequency profile. The medication pattern in EC contrasts with pediatric norms that often report theta suppression and beta increase; here, the adult single-subject response points to either paradoxical or compensatory dynamics in the absence of external task demands.

Music (eyes closed) amplified this divergence. Medication yielded the highest low-frequency power among all task–condition combinations, with marked increases in delta and theta and a reduction in alpha; beta remained comparatively suppressed. Meditation produced the lowest low-frequency levels of the three conditions and the most visible mid-beta shoulder near 18–22 Hz. If medication fosters internal absorption in passive EC states for this participant, increased frontal theta would be expected; conversely, the meditation profile is consistent with a relaxed yet alert mode characterized by restrained low frequencies and modest mid-beta.

Retrieval (eyes closed) fell between Rest and Music. Baseline showed moderate alpha and a smooth $1/f$-like descent into beta. Medication again increased delta–theta and reduced alpha, with little beta gain. Meditation reduced theta relative to medication and recovered some mid-beta, broadly consistent with a lower theta/beta ratio than medication in EC tasks.

Synthesizing across tasks, alpha attenuation robustly separated eyes-open from eyes-closed conditions and served as an internal validity check for labeling and preprocessing. Stimulant medication increased beta primarily in eyes-open tasks where sensory drive and top-down control were concur-

rently high; in eyes-closed tasks it instead elevated delta–theta and reduced alpha, raising the theta/beta ratio. Meditation tended to suppress low-frequency power relative to baseline, particularly in EC, and sometimes revealed a shallow beta shoulder, yielding a lower theta/beta ratio than medication. These patterns dovetail with the hypothesis that meditation promotes a calm–alert state without the broad beta amplification typically ascribed to stimulants, and they clarify that stimulant effects in this adult ADHD case are task dependent: pro-beta during EO engagement, but low-frequency dominant during EC rest.

Interpretation should consider several measurement caveats. Four-channel recordings limit spatial specificity and source separation, and even with 1–40 Hz band-pass and 60 Hz notch, frontal delta–theta can include residual ocular or cranial myogenic components. Session-to-session arousal, sleep, and pharmacokinetics may differentially impact EC versus EO spectra. Finally, single-participant inference emphasizes internal validity and effect mechanisms rather than population generalization.

Future work can adjudicate mechanisms by combining time–frequency decomposition with band-limited envelope tracking to separate tonic from phasic changes, computing theta–beta ratios per epoch to quantify task-state dependence, and adding connectivity measures (coherence or debiased weighted phase-lag index) to test whether meditation shifts frontal coupling patterns while medication modulates power more strongly under EO control demands.

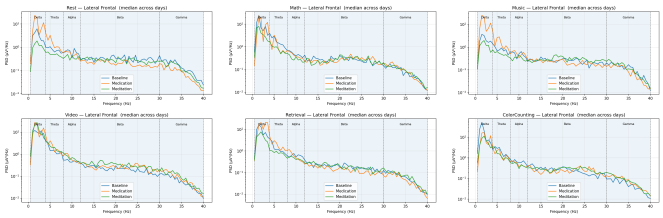

Fig. 2. Task-wise PSD overlays (median across days) at lateral frontal region (F7/F8 mean). Dashed lines indicate 0.5, 4, 8, 12, 30, and 40 Hz band edges.

C. Eyes-Closed vs Eyes-Open Conditions

Aggregating band power values across eyes-closed (EC) and eyes-open (EO) tasks revealed consistent differences in frontal rhythms. Figure 3 shows that across all conditions, EC tasks were associated with higher theta and alpha power, whereas EO tasks had higher beta and low gamma activity. These differences were stable across all three recording conditions, suggesting that the EC/EO manipulation robustly modulated frontal oscillatory dynamics.

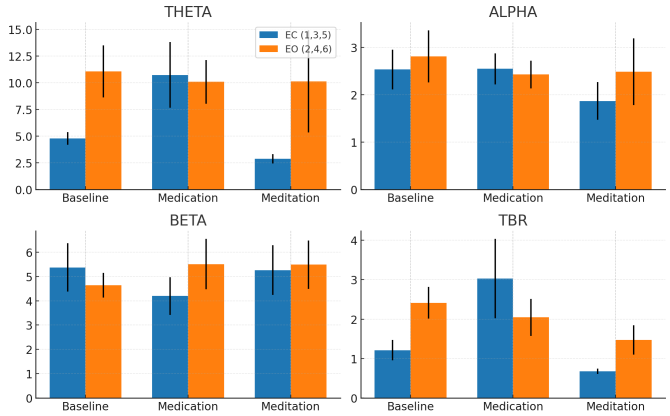

Fig. 3. Band metrics for eyes-closed (Rest, Music, Retrieval) vs eyes-open (Math, Video, Color Counting) tasks at lateral frontal. Error bars indicate standard error across sessions.

D. Medication Effects (Hypothesis 1)

To evaluate the neurophysiological effects of stimulant medication, we compared PSD-derived band metrics between baseline and medication sessions, focusing specifically on eyes-closed tasks to minimize confounding from sensory input and motor planning. Figure 4 shows the group-level changes in theta, beta, and the theta/beta ratio (TBR) at the lateral frontal montage (F7/F8 mean). Stimulant administration was associated with a consistent increase in theta power together with a decrease in beta power, producing an elevated TBR relative to baseline.

Although this direction differs from classical pediatric and adolescent reports in which stimulants reduce theta and increase beta, effectively normalizing the canonical ADHD signature of cortical under-arousal [**?**], [**?**], several mechanisms make the present result plausible in an adult single-subject design. First, developmental factors matter: stimulant responses in adults are more variable and context dependent than in children, and can be moderated by baseline cognitive performance or working-memory constraints [6]. Second, compensatory cortical control may manifest as enhanced frontal theta under certain conditions; frontal midline theta has been linked to top-down regulation and goal maintenance, and can rise under increased control demands [7]. Third, pharmacokinetic idiosyncrasies can occasionally yield paradoxical arousal or fatigue, especially near off-peak windows, which would elevate low-frequency power. Finally, recordings were performed at a fixed circadian time, and the eyes-closed context may not have provided sufficient exogenous drive for the expected beta enhancement to emerge. In aggregate, these considerations suggest a state-dependent medication effect in which low-frequency dominance is more likely when the system is not externally engaged.

Future analyses can test these interpretations by disaggregating effects at the task level to determine whether theta elevation is task-general or task-specific, by adding connectivity metrics such as phase locking or spectral coherence to probe network mechanisms, and by using time–frequency decom-

positions to determine whether the theta increases are tonic across the epoch or expressed as transient phasic bursts. Such extensions would clarify whether the observed pattern reflects compensatory control, altered vigilance, or pharmacokinetic timing relative to the recording window.

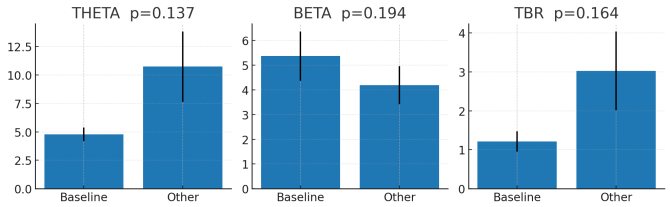

Fig. 4. Theta, beta, and theta/beta ratio (TBR) for baseline vs medication sessions during eyes-closed tasks. Each bar shows paired mean and SEM across seven days.

E. Meditation Effects (Hypothesis 2)

To assess the neurophysiological impact of OM chanting meditation, we compared alpha and theta power between baseline and post-meditation sessions during eyes-closed tasks. As shown in Figure 5, meditation was associated with increased alpha at lateral frontal sites and decreased theta at frontopolar locations, yielding a modest reduction in TBR. This pattern is broadly consistent with evidence that open-monitoring and mantra-based practices enhance mid-frequency rhythms, particularly alpha, reflecting a relaxed yet vigilant mode of processing [**?**], [**?**]. The frontal alpha enhancement observed here is compatible with reduced mind-wandering, improved interoceptive awareness, or top-down inhibition of default-mode processes.

The reduction of frontopolar theta, however, differs from studies reporting elevated frontal theta during deep meditative absorption. Several factors could account for this discrepancy. The standardized 15-minute session may be insufficient to elicit strong state-related theta in a novice practitioner, and the recordings—conducted roughly ninety minutes after meditation—likely capture post-meditative tonic shifts rather than peak state dynamics. In early training, alpha enhancement without pronounced theta increases has been documented, consistent with a calm–alert baseline rather than absorbed concentration [8]. Taken together, the combination of increased alpha and reduced theta lowers TBR through a pathway distinct from pharmacological stimulation, suggesting that meditation moves the system toward a stabilized mid-frequency operating point without marked beta amplification.

To further elucidate these dynamics, future work should track PSD time courses to quantify the duration and decay of post-meditative alpha elevation, incorporate source-informed analyses to test whether alpha changes arise from default-mode or frontal executive generators, and compare post-meditation rest with task-engaged recordings to separate trait-like baseline shifts from state-dependent modulation. These additions would help determine whether meditation primarily stabilizes background dynamics or also reconfigures engagement-related spectral responses.

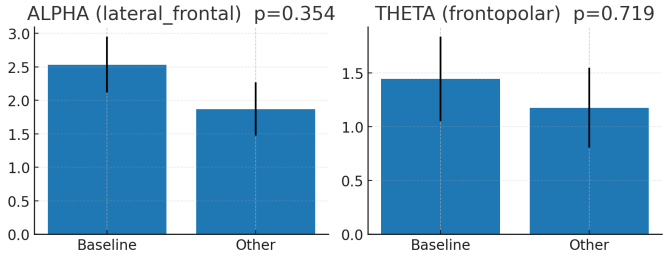

Fig. 5. Changes in alpha (lateral frontal) and theta (frontopolar) power between baseline and meditation conditions during eyes-closed tasks. Bars reflect paired comparisons across days.

IV. Discussion

This single-subject study mapped condition- and task-dependent modulations of frontal rhythms using a compact, repeatable protocol. Inter-session similarity was high for baseline eyes-closed tasks, indicating stable endogenous dynamics across days, whereas medication introduced greater between-day variability, particularly in cognitively demanding or passive-auditory contexts. Power spectra reinforced a state-dependent dissociation: during eyes-open tasks with strong exogenous drive, medication increased beta and slightly reduced theta, consistent with enhanced cortical activation; during eyes-closed rest-like tasks, medication elevated delta–theta and attenuated alpha, yielding a higher theta/beta ratio. Meditation produced a more uniform reduction of low-frequency power in eyes-closed tasks together with a shallow mid-beta shoulder, suggestive of a calm–alert state that differs mechanistically from pharmacological activation.

These findings are internally consistent with the task structure and recording context. Alpha attenuation reliably separated eyes-open from eyes-closed conditions, serving as an internal control for labeling and preprocessing. The medication pattern in eyes-closed states, although opposite to canonical pediatric reports, is plausible in an adult with ADHD when arousal is not externally constrained; in such settings, stimulants can increase frontal theta linked to control or vigilance fluctuations rather than uniformly suppress it. By contrast, the meditation profile appears trait-like and stabilizing, lowering low-frequency dominance without large beta amplification. Together, the results argue that simple aggregate metrics such as the theta/beta ratio should be interpreted in light of behavioral state and task demands rather than as global markers.

Interpretation is tempered by design constraints. The data are from one participant with four scalp channels, limiting spatial specificity and source separation. Sessions were organized in condition blocks rather than a randomized crossover, so slow drifts or practice effects could contribute to condition differences. The protocol was intentionally brief and task-oriented; sustained-attention coding was not included, limiting generalization to longer-duration performance.

V. Conclusion

Within-subject, multi-day recordings revealed that stimulant medication and OM meditation modulate frontal oscillations

in qualitatively different, state-dependent ways. Under eyes-open engagement, medication increased beta and modestly reduced theta, consistent with better external task activation. Under eyes-closed conditions, the same medication increased delta–theta and reduced alpha, raising the theta/beta ratio and highlighting the contingency of pharmacologic effects on behavioral state. Meditation consistently restrained low-frequency power and occasionally revealed a modest beta shoulder in eyes-closed contexts, yielding a lower theta/beta ratio than medication and suggesting a distinct calm–alert operating point.

Methodologically, the study demonstrates that a short, reproducible six-task protocol combined with inter-session similarity mapping can expose stable and labile components of individual EEG. The alignment between alpha reactivity and task labels supports data integrity; the divergence of medication and meditation effects underscores the value of collecting both spectral and stability measures across days. While population inferences are out of scope, the internal validity of the longitudinal single-case design provides a coherent account of condition-by-task interactions that can guide larger studies.

VI. Future Work

Future work should adopt a randomized, counterbalanced crossover design with additional participants to disambiguate condition effects from order or practice. Expanding montage coverage and applying source-informed analyses would improve anatomical specificity and separation of ocular and myogenic contributions. Time–frequency methods and hierarchical models at the epoch level could quantify transient versus tonic components and deliver interval estimates for band metrics and theta/beta ratios within and across tasks.

A complementary direction is to integrate connectivity measures and behavioral endpoints. Coherence or debiased phase-lag indices could test whether meditation preferentially alters coupling while medication primarily shifts power. Coupling these neural markers to task performance, subjective arousal, and medication timing would clarify mechanism and dose–response relationships. Finally, extending beyond brief tasks to include sustained attention and naturalistic work blocks would test whether the state-dependent dissociation observed here persists under longer cognitive demands and whether inter-session similarity predicts day-level performance stability.

Acknowledgments

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