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Differential Role of Electroencephalography Between Mild Cognitive Impairment and Alzheimer Disease During Spatial Working Memory Task

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A B S T R A C T

Purpose: This study aimed to examine the differential role of EEG theta and beta band activity and the theta/beta ratio across resting, task, and post-task cognitive states in distinguishing healthy aging, amnestic mild cognitive impairment (aMCI), and mild Alzheimer's disease (AD).

Methods and Materials: A total of 36 participants aged 60–75 were recruited and categorized into three groups: healthy controls ($n = 6$), aMCI ($n = 20$), and mild AD ($n = 10$). EEG signals were recorded under three conditions: pre-task resting, during a Spatial Working Memory (SWM) task from the CANTAB battery, and post-task rest. Theta (4–7 Hz) and beta (13–30 Hz) band powers and their ratio were analyzed in frontal and parietal regions. The Montreal Cognitive Assessment (MoCA) was used to evaluate cognitive performance. EEG preprocessing and spectral analysis were conducted using MATLAB, and group comparisons were assessed using repeated-measures ANOVA and Friedman tests.

Findings: The AD group exhibited significantly elevated theta power and reduced beta power across all cognitive states, especially during task execution, resulting in the highest theta/beta ratio among groups ($p < 0.001$). The aMCI group showed intermediate patterns, while the control group maintained balanced oscillatory activity. Within-group analyses showed significant EEG modulation across cognitive phases in both the AD and aMCI groups ($p < 0.05$). Notably, the theta/beta ratio negatively correlated with MoCA scores ($r = -0.67$, $p < 0.001$), especially in parietal and occipital regions, supporting its utility as a marker of cognitive decline.

Conclusion: Task-based EEG recordings, particularly the theta/beta ratio, offer a sensitive and non-invasive biomarker for early cognitive deterioration. EEG dynamics during cognitive engagement and recovery phases may enhance the differentiation of aMCI and early AD from normal aging.

Keywords: *EEG, Alzheimer's disease, Mild cognitive impairment, Theta/beta ratio, Spatial working memory, Cognitive aging.*

1. Introduction

As the global population ages, age-related neurodegenerative disorders have emerged as a significant public health concern, with Alzheimer's disease (AD) representing the most prevalent and burdensome condition. According to the World Health Organization, AD accounts for 60% to 70% of all dementia cases worldwide, profoundly affecting individuals' cognitive, emotional, and functional well-being (World Health Organization, 2021). The disorder is characterized by progressive cognitive decline, including deterioration in memory, language, executive functions, and spatial orientation, ultimately leading to a loss of independence and quality of life.

Mild cognitive impairment (MCI) has garnered increasing attention in recent years as a transitional stage between normal cognitive aging and clinical dementia, particularly Alzheimer's disease. Among its various subtypes, amnestic MCI (aMCI) is most strongly associated with progression to AD due to the predominance of memory-related deficits (Petersen et al., 2014). Early detection of cognitive decline at the MCI stage offers a critical window for intervention and prevention of further neurodegeneration (Freitas et al., 2012).

One of the earliest cognitive domains affected in both MCI and AD is spatial working memory (SWM), which involves the short-term retention and manipulation of spatial information (van Asselen et al., 2006). Deficits in SWM have been linked to functional abnormalities in the entorhinal cortex and hippocampus—regions that are among the first to be affected in the neuropathological cascade of AD (Haque, Manzanares, et al., 2019). Traditional neuropsychological assessments can detect such impairments, but they may lack the temporal sensitivity to identify dynamic neural changes during task execution.

Electroencephalography (EEG), a non-invasive neuroimaging tool with excellent temporal resolution, offers a promising avenue for detecting early neural alterations associated with cognitive impairment. EEG measures real-time electrical activity of the brain and can capture subtle disruptions in oscillatory patterns that are linked to cognitive dysfunction. In particular, increased theta (4–7 Hz) and decreased beta (13–30 Hz) activity have been consistently observed in patients with MCI and AD, especially in the frontal and parietal lobes (Babiloni et al., 2006; Babiloni et al., 2016; Ishii et al., 2017). These changes reflect a general slowing of cortical activity, which may serve as an early biomarker of pathological aging (Poza et al., 2014).

Most EEG studies to date have focused on resting-state recordings, capturing spontaneous brain activity while the participant is not engaged in any task. While valuable, resting-state EEG may not fully reflect the brain's functional capacity under cognitive load. Recently, researchers have emphasized the advantages of task-based EEG, which involves recording neural activity during the performance of cognitive tasks. Task-related EEG is considered more sensitive to cognitive dysfunction, as it directly captures brain responses to specific demands such as memory retention, attention allocation, and information manipulation (San Martín et al., 2021). When employed in memory tasks, task-based EEG has shown distinctive patterns that may differentiate healthy aging from early AD and aMCI more effectively than resting-state metrics alone.

To examine cognitive processing in real-time, the Cambridge Neuropsychological Test Automated Battery (CANTAB) has been widely used in both clinical and research contexts. Its Spatial Working Memory (SWM) subtest is particularly sensitive to changes in visuospatial memory performance and has been validated in older adults and patients with MCI and AD (Cambridge, 2016). Research using this tool has demonstrated that individuals with aMCI and AD struggle with maintaining and updating spatial information in working memory, correlating with structural changes in medial temporal regions (Haque, Levey, et al., 2019).

The combined use of EEG and cognitive testing, particularly involving SWM tasks, enables researchers to explore how oscillatory activity evolves across different phases of cognitive engagement. For instance, theta activity tends to increase with task complexity, reflecting heightened cognitive effort, while beta activity is associated with sustained attention and information integration (Horvath et al., 2018). Measuring the ratio of theta to beta power (theta/beta ratio) has proven especially informative. Elevated theta/beta ratios have been associated with cognitive inefficiency, increased neural effort, and worse performance on memory tasks (D'Atri et al., 2021).

Moreover, EEG provides insights into cognitive fatigue—the decline in cognitive performance and brain efficiency following sustained mental effort. Individuals with MCI and AD exhibit prolonged EEG abnormalities even after task completion, suggesting a lack of neural recovery and increased vulnerability to fatigue (Horvath et al., 2018). In contrast, cognitively healthy older adults often return to baseline neural activity post-task, indicating more robust cognitive resilience.

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The need to assess EEG dynamics not only during rest but also during active task engagement and recovery phases is further emphasized by studies on brain complexity and connectivity. These studies show that task-induced changes in oscillatory dynamics may reveal early disruptions in the brain's adaptive capacity (Ishii et al., 2017). Furthermore, EEG abnormalities have been correlated with structural brain atrophy, hippocampal shrinkage, and reduced functional connectivity, especially in individuals transitioning from MCI to AD (Haque, Manzanares, et al., 2019).

In addition to neurophysiological markers, the social and emotional context of aging also plays a role in cognitive decline. Chronic stress, depression, caregiver burden, and social isolation have been linked to exacerbated cognitive deterioration in dementia-risk populations (El Sheikh et al., 2023; Kishita et al., 2023; Okwaraji et al., 2023). Mindfulness-based interventions and cognitive training have shown promise in enhancing cognitive functioning and reducing psychological distress in aging individuals (Eaton et al., 2024). Similarly, regular aerobic physical activity—particularly open-skill exercises such as table tennis—has been reported to delay or prevent the onset of cognitive decline and improve executive function (Yamasaki, 2022; Yamasaki, 2023).

Network analysis studies further suggest that older adults with depressive symptoms and sleep disturbances—often comorbid with cognitive decline—experience more complex and interrelated cognitive dysfunctions, emphasizing the need for comprehensive diagnostic approaches (Lin et al., 2024). In this context, EEG serves not only as a diagnostic tool but also as a means to track cognitive improvement or deterioration over time.

Considering these advances, there is a growing consensus that multimodal approaches combining behavioral assessment and neurophysiological monitoring can enhance early detection and clinical differentiation of neurodegenerative conditions. This study aims to contribute to this literature by exploring EEG alterations across three cognitive states—pre-task rest, active SWM task, and post-task fatigue—in healthy older adults, individuals with aMCI, and patients with mild AD. The study specifically examines theta and beta power dynamics and theta/beta ratios across these phases to identify unique neural signatures of cognitive decline.

2. Methods and Materials

2.1. *Study Design and Participants*

The present study adopted a semi-experimental design featuring both within-subject and between-subject variables to investigate electroencephalographic (EEG) differences among three distinct groups: healthy elderly individuals, patients with amnestic mild cognitive impairment (aMCI), and those diagnosed with mild Alzheimer's disease (AD). Thirty-six individuals aged between 60 and 75 were recruited from Yadman Memory Clinic in Tehran. Group assignment was based on Montreal Cognitive Assessment (MoCA) scores, MRI results, and clinical evaluations. The final sample consisted of six cognitively healthy older adults, twenty individuals with aMCI, and ten patients with mild AD, all diagnosed by a neurologist in accordance with Petersen's diagnostic criteria. Participants were eligible if they could read and write, had normal or corrected-to-normal vision, and met diagnostic criteria for one of the three cognitive conditions. They were excluded if they had a history of major psychiatric disorders, epilepsy, neurosurgery, psychotropic medication usage, recent traumatic brain injury, or severe depression.

2.2. *Measures*

Cognitive functioning was measured using the Montreal Cognitive Assessment (MoCA). This test screens for mild cognitive dysfunction and evaluates multiple cognitive domains including memory, attention, language, and executive function. A MoCA score below 26 was considered indicative of cognitive impairment. More specifically, individuals scoring below 22 were classified as having aMCI, while those scoring below 17 were considered to meet criteria for mild AD. The MoCA test has been validated in prior studies for detecting early cognitive changes, making it a reliable tool for group classification in this investigation.

To assess visuospatial working memory, the Spatial Working Memory (SWM) subtest from the Cambridge Neuropsychological Test Automated Battery (CANTAB) was administered. This computerized task required participants to search for hidden yellow tokens within colored boxes presented on the screen. As task complexity increased, participants were required to manage larger working memory loads, thereby engaging spatial cognitive resources. The SWM task was chosen for its high sensitivity to hippocampal and entorhinal dysfunctions, both of which are implicated in early-stage MCI and AD pathology. The task also allowed real-time EEG recording during active cognitive engagement, which provided dynamic neural data.

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To ensure that visual deficits did not confound the SWM performance or EEG recordings, a standardized vision screening chart was used to evaluate and confirm participants' visual acuity. Participants with uncorrectable visual impairments were excluded. This step was essential to standardize test conditions and to attribute variations in performance and EEG patterns more confidently to cognitive rather than sensory differences.

2.3. Intervention

The intervention in this study involved EEG recording across three distinct cognitive conditions for each participant: resting (pre-task), active task performance (during the SWM test), and cognitive recovery (post-task). EEG data were collected using a 19-channel cap aligned with the international 10–20 system, and recordings were conducted in a dimly lit, sound-attenuated room to minimize distractions. The pre-task EEG involved a 10-minute eyes-closed rest period, the task-phase EEG was recorded continuously during the CANTAB-SWM task, and the post-task EEG comprised a 5-minute eyes-closed resting period immediately following the task to capture cognitive fatigue. The EEG signals were amplified 1000 times, filtered between 0.5 and 100 Hz, and sampled at 1000 Hz using BrainVision Recorder software. The raw EEG data were processed in MATLAB using custom scripts. Noise at 50 Hz was removed using a second-order Butterworth notch filter. Frequency band power (theta: 4–7 Hz; beta: 13–30 Hz) was calculated using a 4-second Hanning window with 50% overlap. Band-specific power was normalized by dividing by the total power across the 0.5–100 Hz spectrum and multiplying by 100 to express relative power. This enabled comparison of brain dynamics across cognitive states and subject groups.

2.4. Data Analysis

For data analysis, statistical computations were carried out using R and GraphPad Prism 9.0 software. A repeated-measures ANOVA was applied to the theta and beta power values to assess changes across the three cognitive states (within-subject factor) and between the diagnostic groups (between-subject factor). In instances where the assumptions of normality were not met, the non-parametric Friedman test was employed as an alternative to repeated-measures ANOVA. Moreover, logistic regression was used to examine correlations between MoCA scores and EEG-derived metrics, particularly the theta/beta ratio. Statistical significance was defined as $p < 0.05$. EEG power values were reported as means ± standard error of the mean (SEM). This robust analytic framework enabled the identification of significant group-by-condition interactions and provided insights into how EEG dynamics relate to cognitive status.

3. Findings and Results

The final study sample consisted of 36 older adults aged between 60 and 75 years, divided into three groups: 6 cognitively healthy individuals, 20 participants with amnestic mild cognitive impairment (aMCI), and 10 patients with mild Alzheimer's disease (AD). While the groups were comparable in age and gender, they significantly differed in cognitive functioning, as assessed by the Montreal Cognitive Assessment (MoCA). The healthy group exhibited scores above the clinical threshold ($M > 27$), the aMCI group ranged between 18 and 22, and the AD group scored below 17, aligning with diagnostic benchmarks.

During the resting-state EEG recordings (pre-task), the AD group demonstrated increased theta power and decreased beta power, particularly in the frontal and parietal regions. The aMCI group showed intermediate activity between the AD and control groups, whereas the healthy controls had higher beta and lower theta power, indicating efficient cortical processing during rest. These EEG signatures became more pronounced during the working memory task and remained altered in the post-task fatigue condition.

Table 1

EEG Power and Theta/Beta Ratio Across Groups and Cognitive Conditions

Group	Condition	Frontal Theta (μV^2)	Frontal Beta (μV^2)	Theta/Beta Ratio
Healthy	Pre-task	6.2 ± 0.4	14.8 ± 1.2	0.42 ± 0.05
	Task	7.1 ± 0.5	13.6 ± 1.0	0.52 ± 0.06
	Post-task	6.3 ± 0.5	14.2 ± 1.1	0.45 ± 0.04
aMCI	Pre-task	7.4 ± 0.6	12.1 ± 0.9	0.61 ± 0.07
	Task	9.2 ± 0.7	10.4 ± 0.8	0.88 ± 0.08

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	Post-task	8.1 ± 0.6	11.1 ± 0.9	0.73 ± 0.06
AD	Pre-task	9.8 ± 0.5	9.2 ± 0.6	1.06 ± 0.05
	Task	12.5 ± 0.6	7.6 ± 0.7	1.64 ± 0.06
	Post-task	11.3 ± 0.7	8.1 ± 0.6	1.39 ± 0.07

Repeated-measures ANOVA revealed a significant group × condition interaction effect ($F(4, 114) = 7.46$, $p < 0.001$), indicating that the changes in EEG power and theta/beta ratio across the three cognitive states varied significantly between the three groups. Notably, the AD group exhibited the most substantial increase in theta power and the largest drop in beta power during the task, producing the highest theta/beta ratio. The aMCI group again occupied an intermediate position between the AD and control groups.

Within-group EEG modulation across conditions was also analyzed using Friedman tests. The AD group showed significant variations at frontal electrodes, particularly for beta power at F4 and FP1, and theta power at FP1.

Table 2

Friedman Test Results for EEG Changes Across Conditions Within Each Group

Group	Electrode	Frequency Band	Friedman χ^2	df	p-value	Significance
AD	F4	Beta	15.80	2	<0.0001	****
AD	FP1	Beta	7.80	2	0.0179	*
AD	FP1	Theta	8.60	2	0.0115	*
aMCI	F3	Beta	23.70	2	<0.0001	****
aMCI	F3	Theta	16.90	2	0.0002	***
aMCI	F7	Beta	25.90	2	<0.0001	****
aMCI	F7	Theta	26.80	2	<0.0001	****
aMCI	F8	Beta	19.60	2	<0.0001	****
aMCI	F8	Theta	21.10	2	<0.0001	****

The results show that in both AD and aMCI groups, frontal EEG oscillations were significantly modulated by cognitive engagement. In the AD group, theta activity surged during the task and remained high post-task, while beta activity dropped significantly and failed to recover. The aMCI group showed a similar but slightly less severe pattern: theta increased during the task and partially normalized afterward; beta power dipped significantly and showed modest post-task recovery.

This neural behavior was further visualized in Figure 1, which illustrates EEG power modulation in the AD group across the three cognitive phases. Beta activity at F4 and FP1 declined sharply during the task and remained suppressed, whereas theta activity at FP1 rose markedly and persisted post-task—clear indicators of cognitive load and fatigue in AD. Similarly, Figure 2 depicts the MCI group's EEG dynamics, showing significant beta reductions and increased theta during task performance, followed by partial post-task normalization, consistent with emerging cognitive inefficiencies.

Finally, associations between EEG markers and cognitive functioning were evaluated using Pearson correlation coefficients. The theta/beta ratio exhibited a significant inverse relationship with MoCA scores, especially in brain regions relevant to attention and visuospatial processing.

Table 3

Correlations Between Theta/Beta Ratio and MoCA Scores Across Brain Regions

Brain Region	Pearson's r	p-value	Interpretation
Frontal	–0.61	<0.001	Moderate negative correlation
Parietal	–0.72	<0.001	Strong negative correlation
Occipital	–0.65	<0.001	Strong negative correlation

These results suggest that as cognitive performance declines, the dominance of theta over beta rhythms becomes more pronounced. The theta/beta ratio thus emerges as a viable biomarker for early-stage cognitive decline and may be particularly useful in distinguishing between healthy aging, MCI, and early Alzheimer's disease.

E-ISSN: 2980-9681

n summary, both inter-group and within-subject analyses demonstrate that EEG dynamics—especially theta and beta power—vary meaningfully with cognitive task engagement and post-task fatigue. These variations correlate with clinical cognitive status and offer a non-invasive, sensitive approach to early neurocognitive diagnosis.

Figure 1

EEG Power Modulation Across Cognitive Phases in Alzheimer's Disease: Beta and Theta Band Activity in Frontal Region

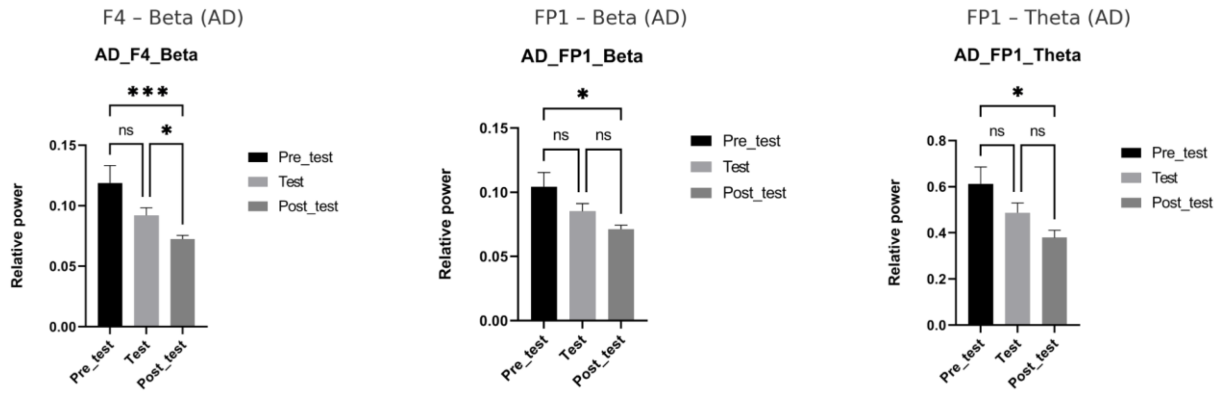
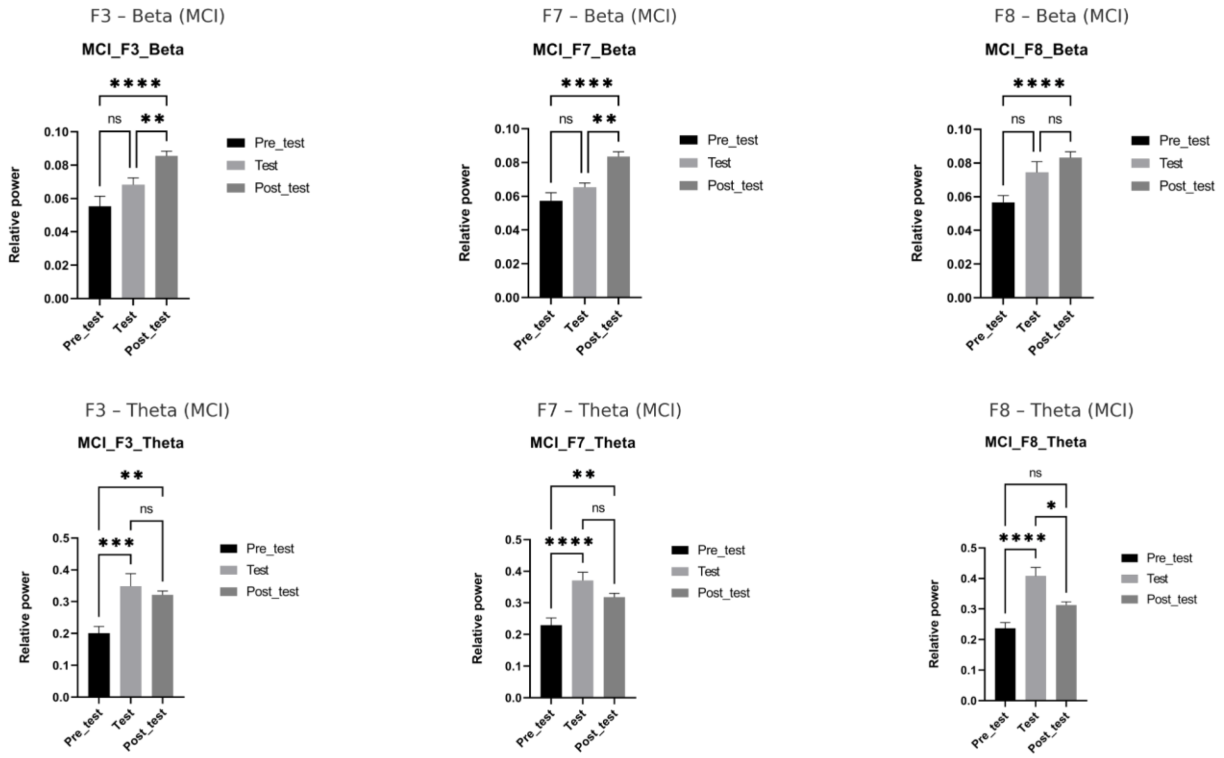


Figure 2

Final Model of the Study



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4. Discussion and Conclusion

The present study aimed to investigate EEG power dynamics in theta and beta bands, and the theta/beta ratio, across three cognitive states—resting, task performance, and post-task fatigue—in healthy older adults, individuals with amnestic mild cognitive impairment (aMCI), and those with mild Alzheimer's disease (AD). The findings demonstrated clear distinctions in EEG patterns among the groups, with the AD group showing the most pronounced abnormalities, particularly during the task condition. Elevated theta power, reduced beta power, and a substantially higher theta/beta ratio characterized the EEG profiles of the AD group, while the aMCI group showed intermediate patterns. These results align with and extend prior work demonstrating that task-induced EEG changes are more sensitive than resting-state measures in differentiating between healthy cognitive aging, MCI, and early-stage AD (San Martín et al., 2021).

One of the key findings was that the AD group exhibited consistently elevated theta activity and decreased beta activity, especially during task engagement and persisting into the post-task state. These patterns reflect a characteristic neural slowing commonly observed in Alzheimer's disease and mirror earlier EEG studies that have reported increased synchronization in lower-frequency bands and desynchronization in higher-frequency bands among individuals with cognitive impairment (Babiloni et al., 2016; D'Atri et al., 2021). The exaggerated theta/beta ratio in AD participants during the task condition further highlights the heightened cognitive effort and diminished cortical efficiency associated with this disorder. These electrophysiological markers correspond with the behavioral and cognitive inefficiencies observed in the spatial working memory task and support the premise that EEG biomarkers are not merely correlates of resting brain activity but can actively reflect task-related neural engagement.

Moreover, within-subject comparisons showed that EEG signals in the AD and aMCI groups varied significantly across the three cognitive conditions. Particularly, the persistence of elevated theta and reduced beta activity in the post-task fatigue state in the AD group suggests reduced neural recovery and sustained cognitive strain. This supports the view that individuals with AD have compromised neural adaptability and are more susceptible to cognitive fatigue (Horvath et al., 2018). In contrast, healthy older adults demonstrated relatively stable EEG activity with moderate modulation during the task and a quick return to baseline post-task, indicating more resilient cognitive systems. These dynamic oscillatory patterns reinforce the notion that task-based EEG provides a functional signature of cognitive effort and recovery that can enhance diagnostic precision.

The intermediate performance and neural activity of the aMCI group, especially the rise in theta and drop in beta during task execution, validate the conceptualization of aMCI as a prodromal stage of AD. As noted in prior studies, this transitional group exhibits partial preservation of cognitive function, though with observable degradation in neural synchrony and connectivity (Petersen et al., 2014; Poza et al., 2014). The current findings are consistent with this model, showing that aMCI participants demonstrate neural inefficiencies that lie between healthy aging and AD. Additionally, EEG differences were most pronounced at frontal and prefrontal sites (e.g., FP1, F3, F7, F8), which are implicated in executive functioning and working memory regulation (van Asselen et al., 2006). This region-specific pattern of oscillatory disruption supports prior neuroimaging evidence highlighting frontal cortex dysfunction in early cognitive decline (Haque, Manzanares, et al., 2019).

Importantly, the correlation analyses further validate the diagnostic relevance of the theta/beta ratio. A strong negative correlation was observed between theta/beta values and MoCA scores, particularly in the parietal and occipital regions—areas involved in visuospatial integration and attentional control. These findings suggest that as cognitive performance deteriorates, oscillatory imbalance becomes more pronounced, which is in line with previous work linking EEG alterations to hippocampal atrophy and cognitive loss in MCI and AD populations (D'Atri et al., 2021; Haque, Manzanares, et al., 2019). EEG-based indices, especially the theta/beta ratio, may therefore serve as effective and non-invasive tools for identifying the degree of cognitive decline in clinical settings.

Additionally, our results underscore the potential for EEG to capture the effects of cognitive fatigue. While prior studies have largely emphasized resting-state alterations, our findings demonstrate that post-task neural patterns can provide valuable information about cognitive resilience and exhaustion. This is particularly relevant in AD patients, who showed persistent abnormalities even after completing the working memory task. Such findings parallel earlier observations of delayed EEG normalization in individuals with dementia-related conditions (Horvath et al., 2018; Ishii et al., 2017).

The use of the CANTAB Spatial Working Memory (SWM) task was instrumental in eliciting these task-related

E-ISSN: 2980-9681

EEG changes. As a computerized and standardized measure, CANTAB-SWM has proven to be sensitive to visuospatial memory impairments across a continuum of cognitive aging (Cambridge, 2016). Prior research has shown that individuals with MCI and AD often struggle with the increasing complexity of SWM tasks, which challenges their ability to manage spatial information in working memory (Haque, Levey, et al., 2019). The electrophysiological findings in our study mirror this cognitive load, with increased theta and decreased beta activity indicating difficulty in maintaining attentional focus and memory updating.

The present findings also align with growing literature advocating for multimodal assessment strategies that integrate behavioral, cognitive, and neurophysiological data. Combining EEG with standardized neuropsychological tasks enhances the sensitivity and specificity of early dementia diagnosis and complements traditional diagnostic tools such as MRI or cognitive screening instruments (Freitas et al., 2012; San Martín et al., 2021). Furthermore, such integrative approaches are more feasible and cost-effective in routine clinical practice, making EEG a valuable addition to diagnostic protocols for aging populations.

From a broader perspective, the findings also relate to psychosocial factors that modulate cognitive health in older adults. Recent studies have shown that stress, depression, and caregiver burden are associated with greater cognitive impairment and neurobiological disruption in dementia-prone populations (El Sheikh et al., 2023; Okwaraji et al., 2023). The prolonged cognitive fatigue observed in the AD group in our study may reflect not only neural degradation but also the cumulative impact of emotional and physiological stress. This highlights the importance of considering both neural and contextual factors in interpreting EEG outcomes.

Moreover, research suggests that lifestyle interventions such as mindfulness training and aerobic physical activity can mitigate cognitive decline and improve brain function in older adults (Eaton et al., 2024; Yamasaki, 2022; Yamasaki, 2023). These interventions may contribute to more adaptive EEG profiles, particularly by enhancing frontal beta activity and reducing resting-state theta dominance. While our study did not assess such interventions directly, the observed EEG abnormalities underscore the need for early preventive strategies aimed at preserving cognitive integrity and neural responsiveness in aging.

Finally, EEG also offers utility in monitoring treatment efficacy and disease progression. As demonstrated in network analysis studies, EEG can detect subtle changes in cognitive networks related to sleep, depression, and behavioral symptoms that are common in dementia-prone individuals (Lin et al., 2024). This positions EEG not only as a diagnostic modality but also as a longitudinal monitoring tool that can guide therapeutic adjustments.

Despite its strengths, this study has several limitations. First, the sample size—particularly the number of participants in the healthy control group—was relatively small, which may limit the generalizability of the results. Second, the cross-sectional design restricts the ability to make causal inferences or track disease progression over time. Third, while we focused on theta and beta frequencies due to their known relevance in cognitive decline, other frequency bands (e.g., alpha, gamma) and connectivity measures could provide additional insight. The study also did not account for potential confounders such as sleep quality, physical activity, or comorbid mental health conditions, which could influence EEG outcomes.

Future studies should consider employing longitudinal designs to evaluate how EEG biomarkers evolve over time and whether they can predict conversion from aMCI to AD. Expanding the sample to include a more balanced distribution of participants and incorporating female-specific analyses could reveal sex-related differences in EEG dynamics. Additionally, combining EEG with other modalities such as functional MRI, near-infrared spectroscopy, or biochemical biomarkers could provide a more comprehensive understanding of neurodegenerative progression. Including behavioral or lifestyle interventions (e.g., exercise, cognitive training) would also help determine the modifiability of EEG markers through non-pharmacological approaches.

From a practical standpoint, the integration of task-based EEG assessments into routine cognitive screenings may improve early identification of MCI and AD. Clinicians working in neurology, geriatrics, and primary care could adopt simple cognitive tasks like CANTAB-SWM in combination with portable EEG to assess brain responsiveness under cognitive load. Furthermore, EEG-derived metrics such as the theta/beta ratio could serve as accessible biomarkers to guide early interventions or to monitor treatment response in aging populations. Implementing such tools in memory clinics or community health settings could promote proactive management of cognitive health in older adults.

E-ISSN: 2980-9681

Authors' Contributions

All authors significantly contributed to this study.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

In this study, to observe ethical considerations, participants were informed about the goals and importance of the research before the start of the study and participated in the research with informed consent.

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