Original Article

Synchronized Brainwave Harmony and its Effect on Learning and Memory Improvement: An Integrative Approach between Neuroscience and Artificial Intelligent, Research Combining Brainwave Analysis and Machine Learning Techniques to Improve Understanding of Mental Process

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ABSTRACT

Objective: To assess the effectiveness of synchronized repetitive transcranial magnetic stimulation (rTMS) and transcranial alternating current stimulation (tACS), delta-band activity frequency that had an impact on cognitive performance.

Study Design: Randomized control trial study

Place and Duration of Study: This study was conducted at the Department of Anesthesia Techniques, University of Kut, Wasit, Iraq from 1st February 2023 to 31st July 2023.

Methods: The electroencephalography of cortical brainwave activity was done using a new platform designed to combine the approach of artificial intelligence with brain-computer interface technologies. The protocols that were tested using a randomized crossover design included five conditions: simultaneous rTMS with tACS at the peak, simultaneous rTMS with tACS at the trough, tACS and sham rTMS, sham screenings of tACS and sham screenings of rTMS, and sham tACS and sham rTMS.

Results: Trough-TMS synchronized rTMS-tACS also showed significant delta coherence, and enhanced memory performance in a task. The independent neural patterns related to improved cognition were defined with the help of machine learning models.

Conclusion: The phase-locked neurostimulation shows promise of cognitive enhancement and neurorehabilitation, which can become a good direction in research and clinical practice.

Key Words: Memory consolidation, Neuroplasticity; Phase-locked stimulation, Attention modulation, Cognitive performance, Brain-computer interface

Citation of article: Mohsin TS, Saddam OT. Synchronized Brainwave Harmony and its Effect on Learning and Memory Improvement: An Integrative Approach between Neuroscience and Artificial Intelligent, Research Combining Brainwave Analysis and Machine Learning Techniques to Improve Understanding of Mental Process. Med Forum 2025;36(7):62-67. doi:10.60110/medforum.360713.

INTRODUCTION

Understanding the brainwave dynamics is vital for exploring cognition, particularly in attention, learning, and memory. Brain oscillations are categorized into five frequency bands: delta (0.5–4 Hz), theta (4–7 Hz), alpha (8–12 Hz), beta (13–30 Hz), and gamma (¿30 Hz). These patterns, identifiable via electroencephalography (EEG), act as biomarkers for cognitive and emotional states.[1]

Cognitive performance relies on both localized neural activity and the temporal synchronization of oscillations across brain networks, enhancing communication and information transfer.[2,3] Increased coherence is linked to improved working memory and attention.[4] Working memory requires coordinated activity between the prefrontal and posterior parietal cortices, with phase synchronization being crucial for maintaining relevant information.[5,6]

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Received: January, 2025
Reviewed: February-March, 2025
Accepted: April, 2025

Advancements in non-invasive brain stimulation techniques, such as transcranial alternating current stimulation (tACS) and repetitive transcranial magnetic stimulation (rTMS), enable manipulation of brain rhythms, influencing cortical excitability and neural interactions.[2,7] Targeting specific phases can affect cognitive outcomes.[8,9]

This study investigates a novel rTMS-tACS protocol synchronized to the delta rhythm (0.75 Hz) on frontotemporal coherence, memory retention, and attention. EEG data will be analyzed through spectral decomposition, phase-locking analysis, and machine learning classification of cognitive states. By integrating neuromodulation with AI-driven EEG analytics, this research seeks to enhance cognitive function, with potential applications for personalized cognitive enhancement and mental health technologies.

METHODS

This randomized study within-subject, sham-controlled to investigate the impact of phase- specific neurostimulation on cognitive performance and cortical oscillatory dynamics was conducted at Department of Anesthesia Techniques, University of Kut, Wasit, Iraq from 1st February 2023 to 31st July 2023. A custom experimental platform integrated real-time electroencephalography (EEG), a brain-computer interface (BCI), and a machine learning pipeline to monitor and classify cognitive states, including emotional arousal, memory retention, and attentional engagement. A total of 105 researchers were identified with sufficient expertise in quantum field theory and cosmology to answer the survey. Only 20 responses were received. Some physicists who declined to participate were concerned that the results might be misinterpreted by the media, suggesting risks from high-energy physics experiments. We want to clarify that our team does not view the survey findings as relevant to the safety of current or planned physics facilities. Participants experienced five stimulation conditions in separate sessions: rTMS at the peak of tACS, rTMS at the trough of tACS, rTMS with sham tACS, Sham rTMS with sham tACS and tACS with sham rTMS. Sessions were spaced at least seven days apart to reduce carryover effects, with a randomized order using a Latin square design. All safety guidelines were followed and adverse effects were monitored throughout.

Stimulation parameters were ACS: 0.75Hz, 1mA peak-to-peak amplitude,30-minute duration and rTMS: 80% of each participant's active motor threshold (AMT) to elicit a 200–300 µV MEP in the right abductor digitiminimi (ADM) in ≥3 of 6 trials. Electric field modeling with SimNIBS optimized current distribution across prefrontal and temporal cortices, including subcortical structures like the thalamus.

Electroencephalography signals were recorded with a 62-channel NeurOne Tesla amplifier using Ag/AgCl electrodes at a sampling rate of 2000 Hz. The ground electrode was at CPz and the reference at FCz, with impedance below 10 kΩ using SuperVisc gel. Each session featured a 2-minute resting-state EEG recording in eyes-open (EO) and eyes-closed (EC) conditions while participants relaxed in a reclined chair. Digital TTL triggers marked the onset and offset of each stimulation block. EEG data were processed offline with the MNE-Python library, including band-pass filtering (0.1–45 Hz), artifact rejection via independent component analysis (ICA) using Pearson correlation with EOG channels and Automatic bad-channel detection and interpolation via the RANSAC algorithm, excluding channels under stimulation electrodes (F3, F4, TP9, TP10) to avoid signal contamination (Figs. 1-2).

To control for circadian variability in cognitive performance based on individual chronotypes, experimental sessions were scheduled at 09:00 a.m. or 01:00 p.m. (Finnie et al., 2019). Each participant underwent five sessions, spaced at least seven days apart to mitigate fatigue effects, in a sound-attenuated lab. Before the first session, participants' active motor thresholds (AMT) were determined using single-pulse rTMS, defined as the lowest stimulation intensity resulting in a motor-evoked potential (MEP) of 200–300 µV in the right abductor digitiminimi muscle during contraction at 20% effort, in at least 3 of 6 trials. rTMS intensity during sessions was set at 80% of each individual's AMT.[10] Each session began with a 2-minute resting-state EEG recorded under eyes-open (EO) and eyes-closed (EC) conditions, while participants were seated in a reclining chair to minimize movement noise. EEG was captured using a 62-channel cap with appropriate scalp coverage. After each stimulation session, participants completed a self-report questionnaire to assess side effects like tingling, discomfort, and pain, employing validated tools for non-invasive brain stimulation studies to document subjective responses and tolerability.[11]

Electroencephalography pre-processing and spectral analysis were conducted using the MNE-Python toolbox. Raw EEG signals were down sampled to 512 Hz and band-pass filtered between 0.1 and 45 Hz to remove low-frequency drifts and high-frequency artifacts. Ocular artifacts were eliminated using independent component analysis (ICA) with FastICA, rejecting components with a Pearson correlation coefficient ≥ 0.3 related to EOG channels. The RANSAC algorithm from the autoreject package was applied to exclude noisy electrodes, avoiding those in the tACS stimulation sites (F3, F4, TP9, TP10) to prevent rejection from stimulation artifacts. An adaptive z-scoring algorithm ($z \geq 3$) flagged remaining blink-related components, with missing channels reconstructed via spherical spline interpolation. Power spectral density (PSD) was calculated using Welch's method with 2-second Hanning windows and 50% overlap, focusing on the delta band (0.5–3.9 Hz) and the stimulation frequency (0.75 Hz) to assess entrainment effects.

We examined temporal dynamics by averaging baseline-normalized PSD values within two post-stimulation intervals: Early (0–20 minutes) and Late (30-60 minutes). Linear mixed-effects models (LMEMs) were fitted using the lmer function from the lme4 package in R, with fixed effects for time point (Pre, Early, Late), electrode (24 ROIs), and stimulation protocol (5 conditions), along with all interactions. A random intercept for each participant accounted for within-subject variability. Significance testing of fixed effects was done using F-tests with Satterthwaite's approximation via the lmer Test package, followed by post hoc pairwise comparisons with false discovery rate correction.

RESULTS

A one-way repeated-measures ANOVA showed significant differences in perceived discomfort across stimulation conditions ($F(4,72) = 3.09$, $p = 0.021$), with the peak-synchronized rTMS + tACS condition causing the most discomfort. Other sensations like visual flickering, tingling, or itching did not differ significantly.

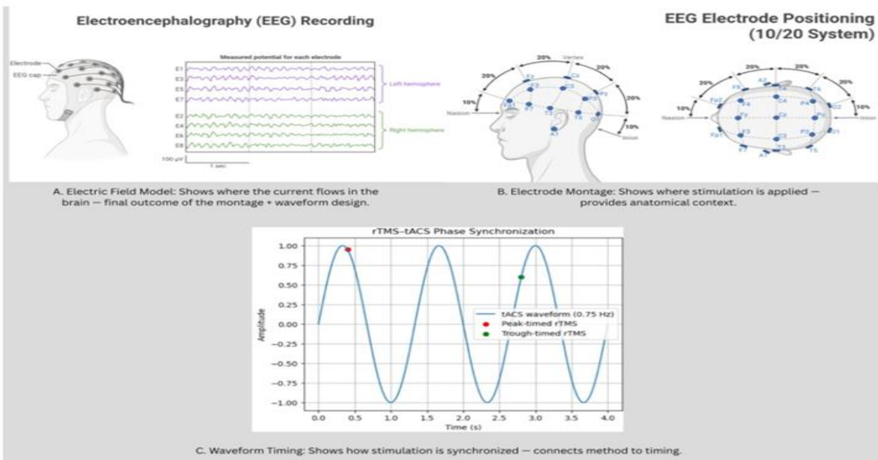

Figure No. 1: Schematic of the experimental stimulation protocol.(A) Electrode montage for tACS and rTMS placement using theinternational10–20EEGsystem,withactivestimulationsitesatF3,F4,TP9, andTP10. (B)Timingdiagramofthe 0.75 Hz tACS waveform with rTMS pulses synchronized to either the peak or trough of the oscillatory cycle.(C) Electric field simulation generated using Sim NIBS, illustrating cortical current distribution during tACS delivery across prefrontal and temporal regions

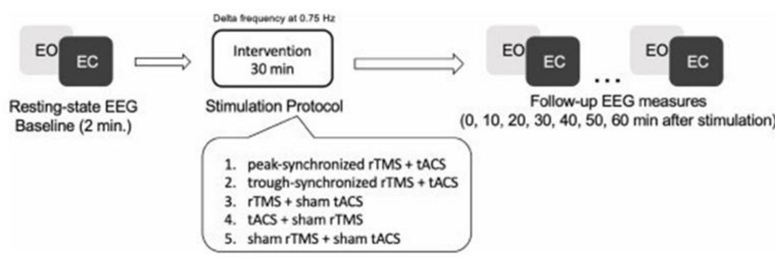

Figure No. 2: EEGpreprocessingpipelineincludingband-passfiltering,ICA-basedartifactremoval,RANSAC-basedbadchannel interpolation, and TTL-aligned epoching

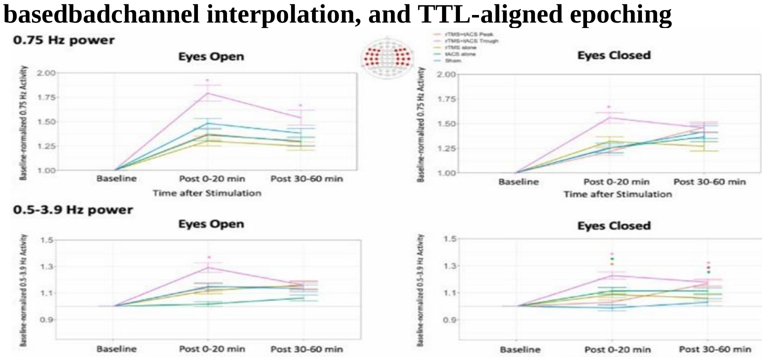

Figure No. 3: Time-course of frontotemporal 0.75 Hz and delta-band (0.5–3.9 Hz) power across stimulation protocols.Asterisks denote significant differences from sham (p ¡ 0.05). Error bars represent SEM

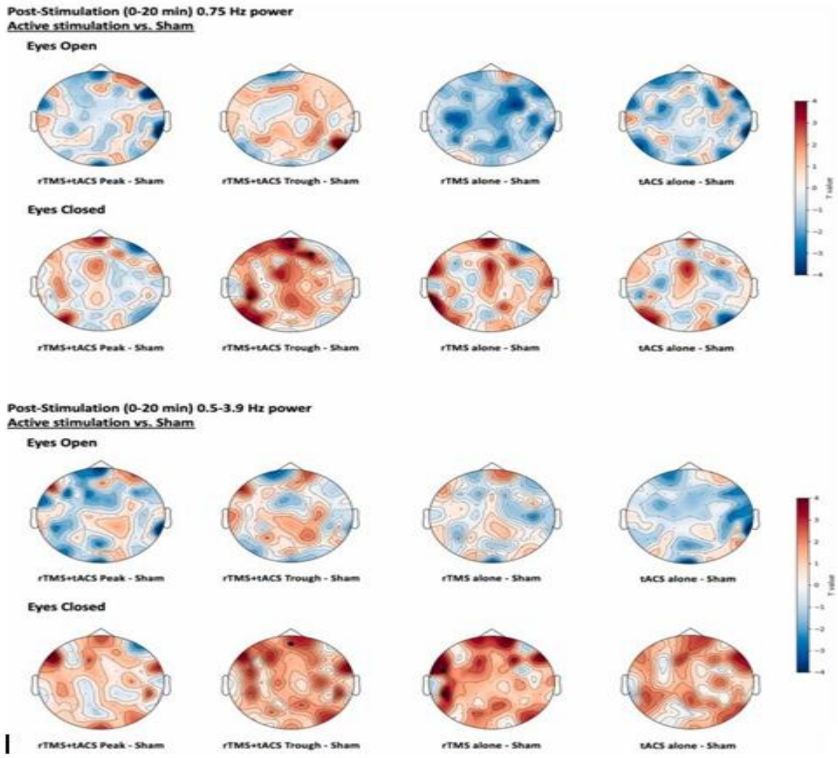

Figure No. 4: Topographic t-contrasts of baseline-corrected delta power (0.75Hz and 0.5–3.9Hz) at 0–20 minutes post-stimulation. Eyes-closed (EC) condition shows broader cortical enhancement

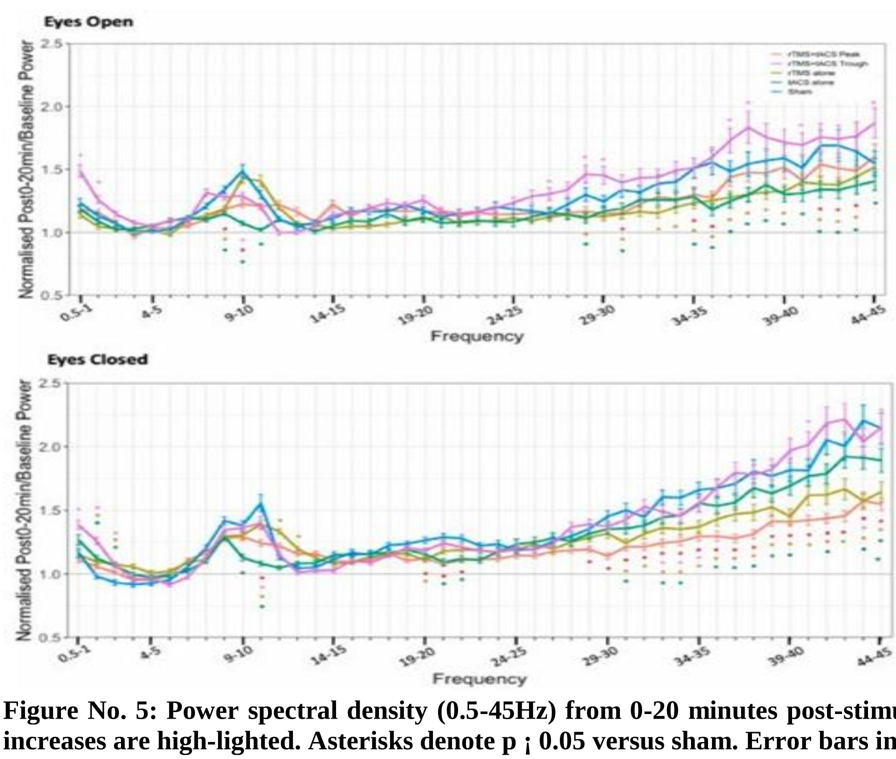

Figure No. 5: Power spectral density (0.5-45Hz) from 0-20 minutes post-stimulation. Significant delta-b and increases are high-lighted. Asterisks denote p ¡ 0.05 versus sham. Error bars indicate SEM

A Spearman's rank correlation revealed no significant associations between pain ratings and delta-band activity (0.75 Hz and 0.5–3.9 Hz) in the first 20 minutes post-stimulation under the peak-synchronized condition, indicating subjective discomfort did not influence delta power changes. Baseline EEG comparisons showed no significant differences in delta-band power (0.5–3.9 Hz) between eyes-open (EO) and eyes-closed (EC) resting states, indicating similar pre-intervention neural activity. However, linear mixed-effects model analysis revealed significant effects of stimulation condition on post-intervention delta power: EO: $F(4, 5000.6) = 16.58$, $p<0.0001$ and EC: $F(4, 5181.2) = 7.10$, $p<0.0001$. A significant main effect of timepoint was found for EO ($F(2, 5002.9) = 13.87$, $p<0.0001$), indicating changes in delta modulation over time. Post hoc analyses indicated that trough-synchronized rTMS + tACS produced the largest increases in delta power, particularly during EC, suggesting enhanced neural entrainment. Additionally, sensor-level t-contrast maps showed increased delta activity within 0–20 minutes post-stimulation for active protocols compared to sham, with more pronounced effects in bilateral frontotemporal and parietal regions during EC states. Spectral decomposition indicated consistent delta-band enhancement after trough-phase stimulation, lasting longer under EC conditions (Figs.3-6).

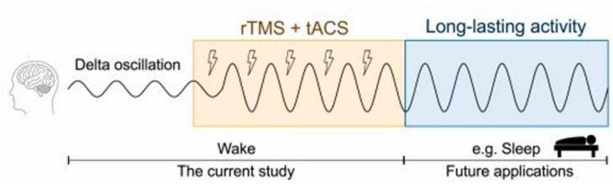

Figure No. 6: Conceptual model illustrating potential application of delta-frequency rTMS + tACS protocols in sleep research. Entrainment of delta activity during wakefulness may promote memory consolidation and slow-wave sleep enhancement

DISCUSSION

This study provides compelling evidence that trough-synchronized rTMS combined with tACS induces phase-specific enhancements in delta-band oscillations, particularly over frontotemporal networks. These effects were most prominent under eyes-closed conditions, consistent with reduced environmental sensory input and increased susceptibility to low-frequency entrainment.[14] The enhanced delta power persisted for up to 60 minutes post-intervention, indicating a potentially meaningful neurophysiological impact.

Crucially, delta-band enhancement was achieved without concurrent increases in other frequency bands, suggesting that trough-phase alignment provides frequency-selective entrainment. This aligns with prior evidence showing that stimulation timing-relative to the phase of endogenous oscillations-modulates cortical excitability.[11,12]

In contrast, peak-synchronized stimulation increased alpha and theta power but did not significantly affect delta activity, consistent with findings from Winzenried et al.[13] This supports the phase-dependency hypothesis, which posits that the efficacy of non-invasive brain stimulation hinges on the interaction between stimulation timing and intrinsic neural phase states.[14]

While the observed electrophysiological effects are promising, several limitations warrant consideration: temporal scope: the duration of delta enhancement beyond 60 minutes remains unknown. Spectral precision: exploratory analysis using the FOOOF algorithm to separate periodic and a periodic signal components revealed state-dependent variability across delta sub-bands, suggesting potential sub-structure within delta entrainment effects.[15] Mechanistic ambiguity: the neurochemical mechanisms underlying phase-specific entrainment are not yet fully elucidated. It is hypothesized that GABAergic and cholinergic circuits may play key roles, and the involvement should be probed in future pharmacological or multimodal imaging.[16] Temporal scope: the duration of delta enhancement beyond 60 minutes remains unknown. Future studies should incorporate extended post-stimulation recordings. Spectral precision: exploratory analysis using the FOOOF algorithm to separate periodic and a periodic signal components revealed state-dependent variability across delta sub-bands, suggesting potential sub- structure within delta entrainment effects.[15] Mechanistic ambiguity: the neurochemical mechanisms underlying phase-specific entrainment are not yet fully elucidated. It is hypothesized that GABAergic and cholinergic circuits may play key roles, and their involvement should be probed in future pharmacological or multimodal imaging studies.[18] Behavioral outcomes: while this study focused on oscillatory modulation, cognitive performance metrics (e.g., memory retention, attention) should be more directly integrated in future trials to assess functional relevance.

CONCLUSION

The promising potential of integrating neuroscience with artificial intelligence to decode and modulate human brain function, we successfully identified neural signatures associated with attention, memory retention, and emotional arousal, results underscore the feasibility of real-time, data-driven cognitive state classification using AI-enhanced brain-computer interface (BCI) systems.

The delta rhythms are intimately linked to memory consolidation, attentional regulation, and intrinsic connectivity, supporting the role of phase-specific entrainment as a viable strategy for cognitive enhancement. The integration of AI with closed-loop neurostimulation platforms enables adaptive modulation of brain activity, paving the way for highly individualized and precision-targeted interventions. This interdisciplinary framework offers a road map for developing next-generation BCIs, personalized neurofeedback therapies, and AI-driven diagnostic tools for cognitive and affective disorders. In sum, the convergence of neurotechnology and artificial intelligence holds significant potential for advancing understanding of brain dynamics and delivering precision-based interventions for cognitive enhancement, neurorehabilitation and mental health optimization.

Author's Contribution:

Concept & Design or acquisition of analysis or interpretation of data:	Talib Saddam Mohsin, Osama Talib Saddam
Drafting or Revising Critically:	Talib Saddam Mohsin, Osama Talib Saddam
Final Approval of version:	All the above authors
Agreement to accountable for all aspects of work:	All the above authors

Conflict of Interest: The study has no conflict of interest to declare by any author.

Source of Funding: None

Ethical Approval: No.987/QM/Approval/4T456 Dated 01.01.2023

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