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RESEARCH ARTICLE

Amplitude and Phase Synchronization Stability of Auditory Evoked Potentials with Influence of Transcranial Magnetic Stimulation

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Abstract The integration of Transcranial Magnetic Stimulation (TMS) with Electroencephalography (EEG) offers a robust framework for investigating brain function and underlying neural mechanisms. While most TMS-EEG studies have focused on TMS-evoked potentials (TEPs) to examine the immediate cortical effects of TMS, limited attention has been given to its influence on the auditory cortex, particularly in terms of how long the modulation persists. This study aims to analyze the effects of TMS on Auditory Evoked Potentials (AEPs), with a focus on changes observed 1 and 2 seconds after stimulation. Single-pulse TMS was applied with a 4-second interstimulus interval (ISI) and presented simultaneously with auditory stimuli delivered at a 1-second ISI. The influence of TMS on AEPs was assessed using time-domain averaging and phase synchronization stability analysis. Results showed minimal differences in the averaged N100 and P200 components between TMS and sham conditions at 2 seconds post-stimulation with ANOVA p=0.08. However, phase stability analysis revealed significantly higher synchronization in the N100 wave 1 second after TMS ANOVA p=0.01, followed by increased stability in the P200 and P300 components compared to the sham condition. These findings highlight the importance of advanced analytical techniques in detecting subtle and transient neural changes induced by TMS. By providing insights into the temporal characteristics of TMS-modulated auditory processing, this study contributes to the development of more targeted diagnostic and therapeutic applications involving non-invasive brain stimulation.

Keywords: Auditory evoked potentials, electroencephalography, Anacardium occidentale, Transcranial Magnetic Stimulation.

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Introduction

Transcranial Magnetic Stimulation (TMS) is a non-invasive neuromodulation technique that has shown considerable promise in modulating neural activity and treating various neurological and psychiatric disorders [1]. By delivering brief magnetic pulses to specific brain regions, TMS can influence neural circuits and alter brain function. This technique has been utilized in both research and clinical settings to study brain connectivity, cortical excitability, and the mechanisms underlying neuroplasticity.

TMS has been proven as a clinical diagnostic utility in various neurological and psychiatric disorders, including myelopathy, amyotrophic lateral sclerosis (ALS), multiple sclerosis (MS), cerebellar disease, dementia, facial nerve disorders, movement disorders, epilepsy, migraine, and chronic pain [2]. One of the most robust and widely accepted uses of TMS is in measuring the connection between the primary motor cortex and a muscle. Central Motor Conduction Time (CMCT) is a sensitive method for detecting cord compressions in myelopathy, upper motor neuron involvement in ALS, and identifying lesions in MS.

The effect of TMS has also been examined in numerous clinical applications, such as tinnitus [3], stroke [4], Parkinson's disease [5], Alzheimer's disease [6], traumatic brain injury [7], and attention-deficit/hyperactivity disorder (ADHD) [8]. Extensive therapeutic TMS research has been conducted in the field of psychiatry, particularly in major depression, demonstrating the statistical significance of TMS over placebo [9]. Therapeutic TMS has been accepted as a standard treatment for depression in many countries.

This therapeutic evidence on the effects of TMS on various diseases indicates that TMS directly or indirectly induces changes in cortical processing. Several studies discuss the effect of TMS on the neuroplasticity of the brain [10]. Furthermore, the effects of TMS on cognitive functions and attentional processes have been reported in numerous studies [11]. These studies demonstrate that single-pulse TMS can facilitate cognitive processes.

TMS combined with electroencephalography (EEG) has emerged as a powerful tool for investigating cortical excitability and connectivity. This methodology allows researchers to explore the dynamics of brain networks in both healthy individuals and those with various neuropsychiatric disorders. The integration of TMS and EEG enables the measurement of TMS-evoked potentials (TEPs), which provide insights into the excitatory and inhibitory processes within the cerebral cortex [12].

The utility of TMS-EEG extends to the identification of biomarkers for psychiatric conditions. For instance, studies have shown that specific TEP metrics, such as the N100 and long-interval intracortical inhibition (LICI), correlate with treatment-resistant depression (TRD) severity and suicidality [13,14]. Furthermore, TMS-EEG has been employed to assess cortical dysfunction in schizophrenia, revealing unique neurophysiological signatures that differentiate it from other disorders like depression and anxiety [15]. This specificity is crucial for developing targeted interventions and understanding the underlying pathophysiology of these conditions.

Moreover, TMS-EEG has been involved in elucidating the effects of various stimulation protocols on cortical activity. For example, studies utilizing intermittent theta burst stimulation (iTBS) have demonstrated that TEPs can reveal central effects not captured by traditional motor-evoked potentials (MEPs) [16]. This highlights the potential of TMS-EEG to provide a more nuanced understanding of cortical dynamics, particularly in clinical populations such as stroke patients, where altered excitability patterns have been observed [17,18].

In addition to clinical applications, TMS-EEG research has contributed to the understanding of fundamental neurophysiological processes. The technique allows for the exploration of large-scale network dynamics and the assessment of how different brain regions interact following TMS [19]. For instance, the study of TMS-evoked responses has revealed insights into the excitatory/inhibitory balance within cortical circuits, which is essential for understanding cognitive functions and plasticity [14].
Auditory evoked potentials (AEPs) are critical components in the study of brain responses to auditory stimuli, particularly in the context of TMS combined with EEG. The TMS pulse generates a loud clicking sound that can elicit AEPs, complicating the interpretation of TMS-EEG data. This is because the auditory stimuli can produce responses that overlap temporally with the TEPs, leading to potential confounding factors in the analysis of cortical excitability and connectivity [20,21].

Research has also indicated that the timing of auditory stimuli relative to TMS can significantly influence the observed AEPs. For example, auditory stimuli presented shortly after TMS can evoke mid-latency peaks in AEPs, which may obscure the interpretation of TEPs [22,23]. This temporal overlap necessitates careful experimental design to ensure that the contributions of auditory stimuli are adequately controlled. Furthermore, the potential for AEPs to dominate the TEP recordings underscores the importance of developing robust methodologies for artifact rejection and signal separation in TMS-EEG studies [24,25].

The implications of AEPs in TMS-EEG research extend to clinical applications, where understanding the interplay between auditory processing and cortical excitability can inform treatment strategies for various neuropsychiatric conditions. For instance, alterations in AEPs can be indicative of central auditory processing disorders, which may co-occur with other neurological conditions [26,27]. Thus, integrating AEP analysis within TMS-EEG frameworks can provide valuable insights into the neural mechanisms underlying auditory perception and its relationship with motor and cognitive functions [28,29].

Several studies have shown promising results using TMS in clinical applications [1]. However, there are very limited studies on applying TMS to the auditory cortex, especially in combination with EEG studies[30,31]. Most research focuses on the motor cortex or frontal lobe. Studying TMS effects on the auditory cortex may provide new insights into EEG and auditory processing.

Most TMS-EEG studies have focused on the direct effects of TMS on EEG by analyzing TEPs, which primarily indicate short-term effects in milliseconds, such as N100 and P300. To examine the longer-term effects of TMS, introducing a secondary stimulation, such as an auditory stimulus after TMS, and analyzing the secondary evoked potential can be insightful. This approach may illuminate the effects of TMS several seconds after stimulation.

In event-related analysis, the averaging of EEG responses to stimuli is typically used to overcome the low signal-to-noise ratio in EEG signals. The timing of these responses provides a measure of brain communication timing or information processing time. However, the averaging technique requires a large number of responses to obtain reliable event-related potential (ERP). In some cases, such as TMS-ERP measurements for safety reasons, the required number of responses cannot be obtained [32]. One solution to this problem is to analyze the trend within the responses, such as single epoch tracing and phase synchronization stability of the responses [33].

The aim of this paper is to investigate the influence of TMS-EEG on auditory processing, particularly focusing on how TMS can modulate neural activity within the auditory cortex and the implications for auditory perception. The AEP within the auditory cortex is assumed to be modulated by the TMS not only immediately but also after a certain duration. The phase synchronization stability measure is used to extract the AEP immediately after TMS and the AEP after one second of TMS and compare them with AEPs without TMS.

Materials and Methods

Experimental Procedure

This study involved ten student volunteers (aged 23–30 years; 7 males, 3 females) with normal hearing and no history of neurological disorders. Informed consent was obtained from all participants prior to their involvement in the study. During the experiment, participants were instructed to close their eyes and sit in a reclining chair to minimize head movement artifacts. A figure-eight TMS coil (Magstim Super Rapid System) was placed over the left temporal lobe, while auditory stimuli were presented to the right ear through headphones. Four Ag/AgCl EEG electrodes were positioned: two on the left and right mastoids, one at the vertex (reference), and one on the upper forehead (ground). The experimental setup is described in Figure 1. To ensure data quality, electrode impedances were strictly maintained below 5kΩ throughout all measurements.

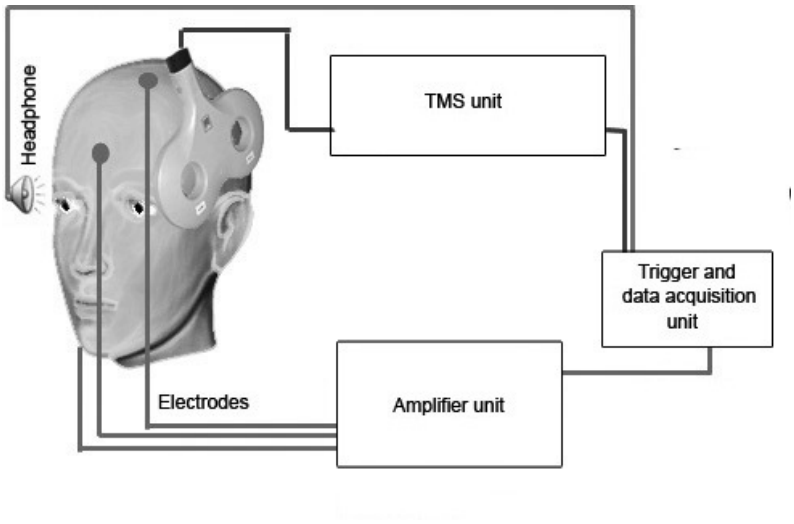


Figure 1. Block diagram of TMS-AEP experiment

TMS intensity was set at 100% of the individual motor threshold (MT). MT was determined by repeatedly stimulating the left motor cortex, gradually increasing TMS intensity and adjusting the coil position until a twitch in the right finger was observed. Auditory stimuli consisted of three pure tones (1 kHz, 1.5 kHz, and 2 kHz) presented in a randomized order, each with a duration of 50 ms and a rise/fall time of 10 ms.

Single-pulse magnetic stimulations were applied with a 4-second interstimulus interval (ISI) and presented simultaneously with auditory stimuli, which had a 1-second ISI (as depicted in Figure 2). This simultaneous presentation of TMS and auditory stimuli was designed to evaluate the influence of TMS on the auditory cortex. In total, the subject received 50 TMS stimuli paired with auditory pure tones, along with 150 auditory pure tone stimuli without TMS.

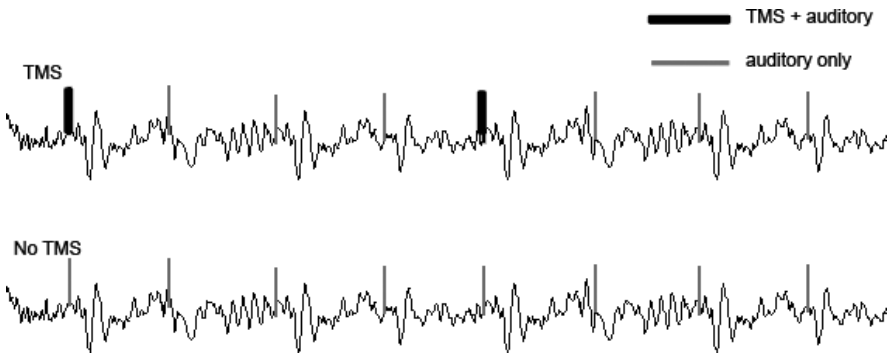


Figure 2. Sequence of the TMS and auditory stimulation

The TMS coil's loud click could potentially induce auditory evoked potentials, leading to unwanted additional auditory stimulation. To mitigate this, headphones were used to dampen the click sound, which was further masked by the auditory pure-tone stimulation. The TMS coil was positioned on the scalp with a slight gap to prevent vibration and bone conduction to the scalp and auditory pathway. Magnetic stimulation can also distort EEG recordings by producing large magnetic artifacts. While this complication was unavoidable, the artifacts were removed during EEG preprocessing.

Subjects were required to detect predetermined target tones and respond by pressing a button to maintain alertness and reduce habituation effects. The auditory and magnetic stimulus interval remained constant throughout the experiment to assess the effects of TMS on auditory evoked potentials at specific time intervals. All subjects were required to detect target tones with at least 50% accuracy. The experiment was repeated with sham TMS to record normal auditory evoked responses for comparison with TMS-AEP recordings. During these control trials, the TMS coil was positioned away from the subject's head to exclude magnetic stimulation while maintaining the click sound.

EEG signals were measured using a g.USBamp system (Guger Technologies Austria), which has an input range of ± 250 mV, allowing for the recording of DC signals and TMS spikes without saturation. The sampling frequency was set to 512 Hz. Signals were not filtered during measurement to avoid filter aliasing effects caused by the high frequency of TMS evoked spikes.

Signal Preprocessing

Magnetic artifacts were observed in the EEG signals within 20 ms post-stimulation. Filtering the large artifact with limited sampling frequency will generate ripples surpassing 40 ms after the stimulation and contaminates the informative potentials as illustrated in Figure 3. To mitigate the impact of these high-frequency artifacts, a signal mirroring technique was employed. This technique involves replacing the artifact-containing portion of the signal (within 40 ms post-stimulation) with a mirrored version of the pre-stimulus signal, as illustrated in Figure 4. This method effectively removes TMS artifacts without compromising the informative potential of the signal after 40 ms. The EEG signals were then bandpass filtered (cutoff frequencies: 1 Hz - 30 Hz) and segmented into evoked potentials ranging from 200 ms pre-stimulus to 800 ms post-stimulus for each TMS and auditory stimulation.

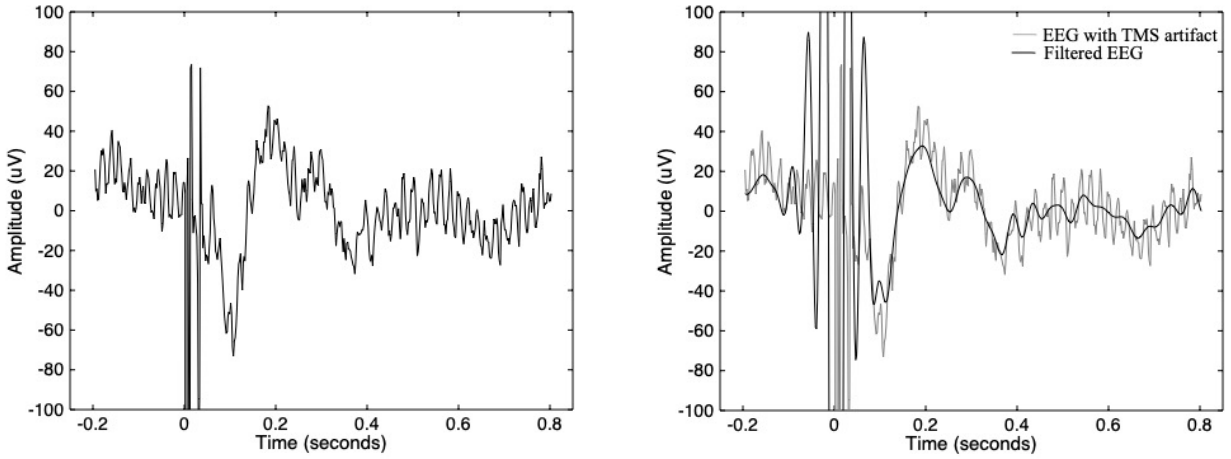


Figure 3. (a) EEG signal with large amplitude TMS artifact upon TMS stimulation and (b) filtered EEG signal with additional large ripples due to TMS artifact

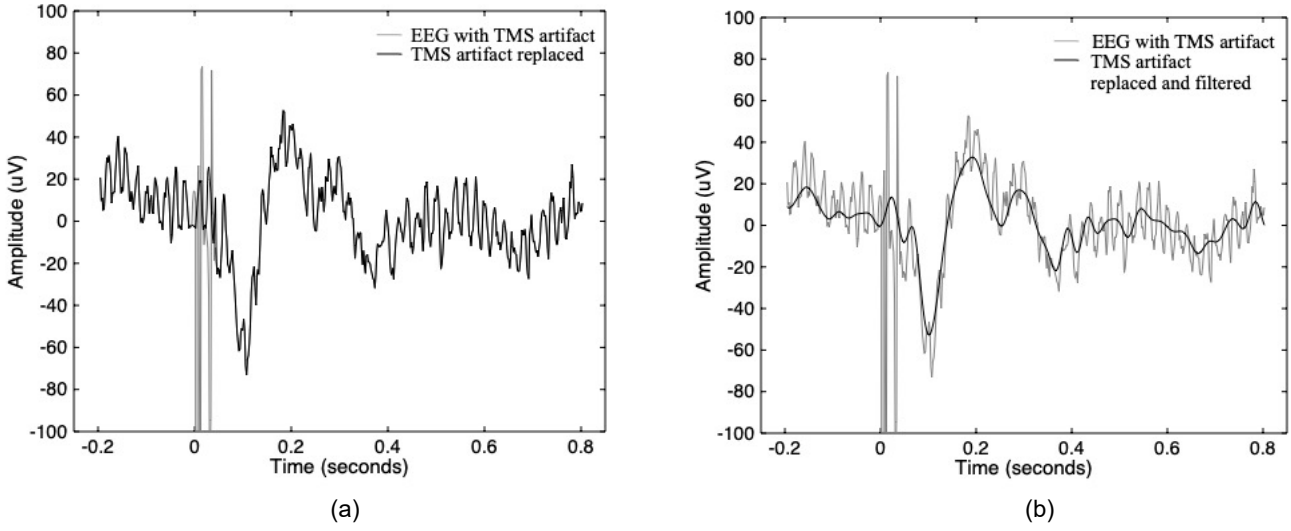
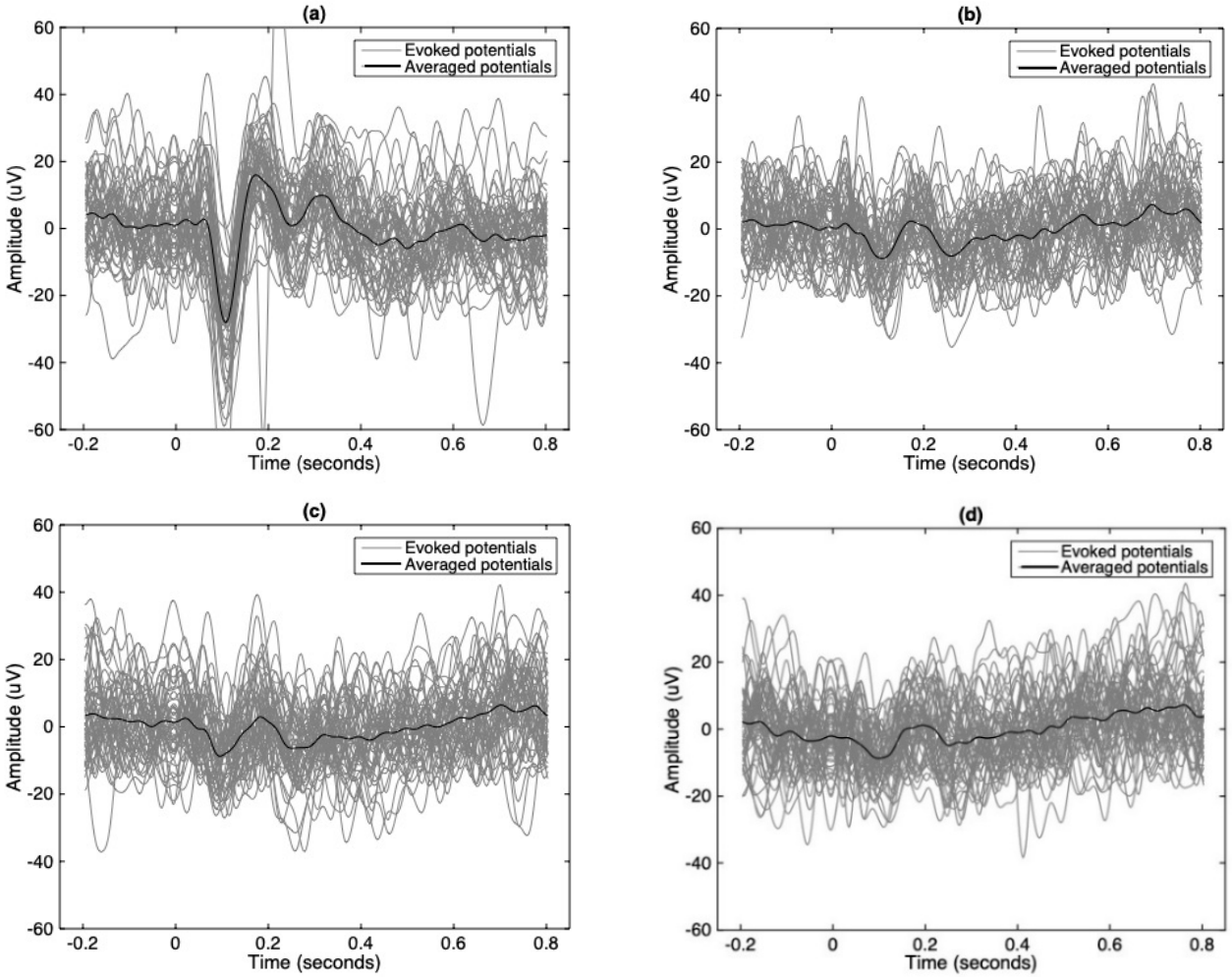


Figure 4. (a) TMS high-frequency artifact replaced by mirrored pre-stimulus signal and (b) Smooth EEG signal after TMS artifact replaced and filtered

Signal Averaging

The segmented evoked potentials were arranged into four groups: group 1 consisted of the TEPs and AEPs segmented within 1 second after TMS and auditory stimuli, group 2 consisted of the AEPs segmented between 1 to 2 seconds after TMS, group 3 consisted of the AEPs segmented between 2 to 3 seconds after TMS, and group 4 consisted of the AEPs segmented between 3 to 4 seconds after TMS. As a result, each group consisted of 50 epochs of TEPs+AEPs or AEPs with a similar TMS latency effect. Another four groups for sham TMS were also created from the control experiment to compare the difference between TMS and sham TMS evoked potentials. The sample of the evoked potentials for one subject is illustrated in Figure 5. Subsequently, the potentials were averaged within each group to obtain the ERP. The averaging of the potentials reduced the unsynchronized potentials and illuminated the evoked potentials. Moreover, the averaged potentials generated from the signals throughout the EEG recording also reduced the effect of habituation.



(a) (b)

Figure 5. (a) 50 epochs and averaged TEPs+AEPs segmented within 1 second after TMS, (b) AEPs segmented between 1 to 2 seconds after TMS, (c) AEPs segmented between 2 to 3 seconds after TMS and (d) AEPs segmented between 3 to 4 seconds after TMS

Phase Synchronization Stability

The Wavelet Phase Synchronization Stability method is used to assess the consistency of phase responses across multiple EEG trials. Unlike traditional time-domain averaging, which primarily emphasizes amplitude, the approach captures the stability of phase alignment at specific time–frequency points. This method involves applying a continuous wavelet transform (CWT) to each EEG epoch to extract time-resolved phase information. For each time point and frequency, the phase values across trials are computed and compared using phase-locking metrics. Higher values indicate greater consistency or synchronization in the neural response phase across trials, reflecting increased neural phase stability. In this study, this method was applied to evaluate the temporal dynamics of AEPs following TMS, allowing for the detection of subtle TMS-induced modulations in cortical synchronization that may not be apparent through amplitude-based measures alone.

To determine the synchronization stability of signals, an adaptation of the derived phase locking measure is required between the two signals following notation by Strauss ***et al***. [34]. Let $\psi_{a,b}(\cdot) = |a|^{-1/2}\psi\big((\cdot - b)/a\big)$ where $\psi \in L^2(R)$ is the wavelet with:

$$0 < \int_{\mathbb{R}} |\Psi(\omega)|^2 |\Psi(\omega)|^{-1} d\omega < \infty \qquad (1)$$

Here $\Psi(\cdot)$ is the Fourier transform of the wavelet, and $a, b \in \mathbb{R}, a \neq 0$). The wavelet transform:

$$\mathcal{W}_\psi: L^2(\mathbb{R}) \longrightarrow L^2\left(\mathbb{R}^2, \frac{da\, db}{a^2}\right) \quad (2)$$

of a signal $x \in L^2(\mathbb{R})$ with respect to the wavelet ψ is given by the inner L^2 -product:

$$(\mathcal{W}_\psi x)(a,b) = \langle x, \psi_{a,b} \rangle_{L^2} \quad (3)$$

In this study, the sixth derivative of the complex Gaussian function is used as the wavelet. Note that the scale a can always be associated with a 'pseudo' frequency f_a in Hz by:

$$f_a = f_\psi / aT \quad (4)$$

where T is the sampling period, i.e., the inverse of the sampling frequency, and f_ψ is the center frequency of the wavelet ψ.

The synchronization stability $\Gamma_{a,b}$ of a $\mathcal{X} = \{x_m \in L^2(\mathbb{R}): m = 1, \ldots, M\}$ of M sweeps is defined by:

$$\Gamma_{a,b}(\mathcal{X}) \coloneqq \frac{1}{M}\left|\sum_{m=1}^{M} e^{i \arg\left((\mathcal{W}_\psi x_m)(a,b)\right)}\right| \quad (5)$$

The synchronization stability as evaluated by the wavelet phase stability is a value between 0 and 1. A perfect synchronization stability for a particular a' and b' for $\Gamma_{a',b} = 1$ (perfectly coherent phases) can be obtained and a decreasing stability for smaller values due to phase jittering. The phase $\arg((\mathcal{W}_\psi y)(a,b)$ of a virtual reference signal y is constant for all m in scale and time. Then the phase difference can be obtained as:

$$e^{\iota(\arg(\mathcal{W}_\psi x_m)(a,b)) - \arg((\mathcal{W}_\psi y)(a,b)))} \quad (6)$$

but the result for the stability remains the same. This experiment shows the relation of the stability criteria to phase locking measures of two signals and oscillators.

Results and Discussion

Phase Stability Scale Selection

Figure 6 provides a visual representation of phase stability for TEP of a subject. The gradient values in Figure 6(a) indicate the degree of synchronization between evoked potentials for different scales of wavelet. Values closer to 1 suggest higher synchronization, while values closer to 0 indicate lower synchronization. Figure 6(b) shows the one-dimensional phase stability signal for a selected wavelet scale of 40. This analysis clearly demonstrates that TEPs exhibit the highest phase synchronization within the first 200 milliseconds following stimulation.

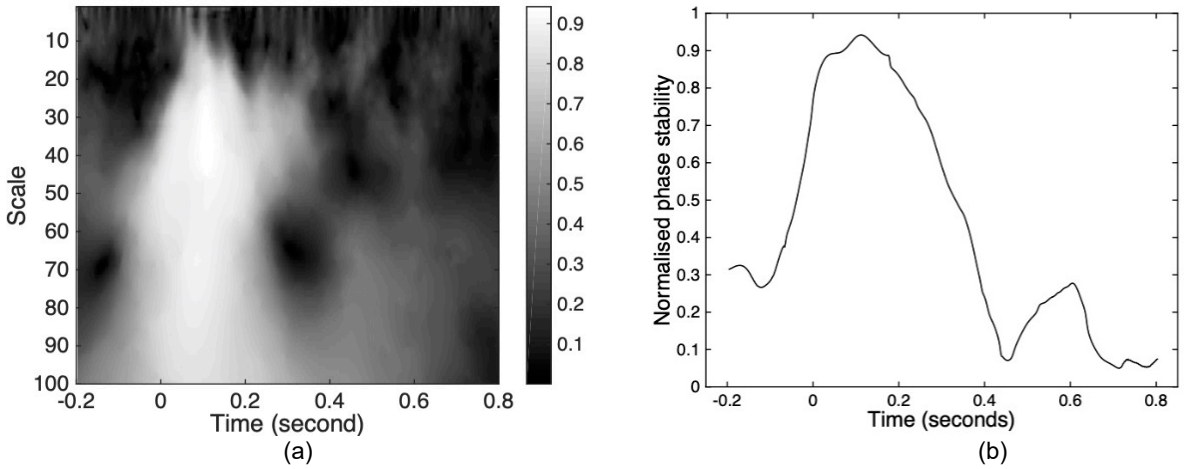


Figure 6: (a) Phase stability of TMS evoked potential of one subject with scales from 1 to 100 and (b) the phase stability with a selected scale of 40

TMS Evoked Potential

Figure 7(a) shows the grand average evoked potential of all subjects where the TMS effects are obviously seen in N100-P200 waves and P300 waves. The normal auditory evoked potentials can be seen in both averaged signals with and without TMS even though the potentials were averaged from low number of trials (i.e., 50 trials). In addition, the result of the averaged evoked potential in all subjects demonstrated that there were immediate cortical excitations affected by TMS stimulated on the temporal region of the brain specifically in auditory cortex. The result shown in this experiment is clear evidence that the N100-P200 waves in auditory cortex were increased by magnetic stimulation.

In addition, the magnetic stimulation also contributes to the increased P300 component as shown in grand averaged evoked potentials in Figure 7(a). The P300 component is widely used to indicate the attention level of the subject and often elicited using a simple discrimination task with auditory or visual stimulation [35]. Thus, it is suggested that TMS also increases the attention of the subject to auditory stimulation.

Figure 7(b) illustrates the average evoked response and phase stability of the combined TEP+AEP signal compared to the sham TMS+AEP signal for ten subjects at a wavelet scale of 40. The results indicate significant synchronization around 100-200ms and 300ms post-TMS. Notably, a phase stability value closer to 1 signifies higher synchronization across trials. The measure provides insight into the degree of neural synchronization at different latencies, which can be affected by TMS. Thus, the phase stability measure offers a promising feature extraction technique in addition to the averaging methods.

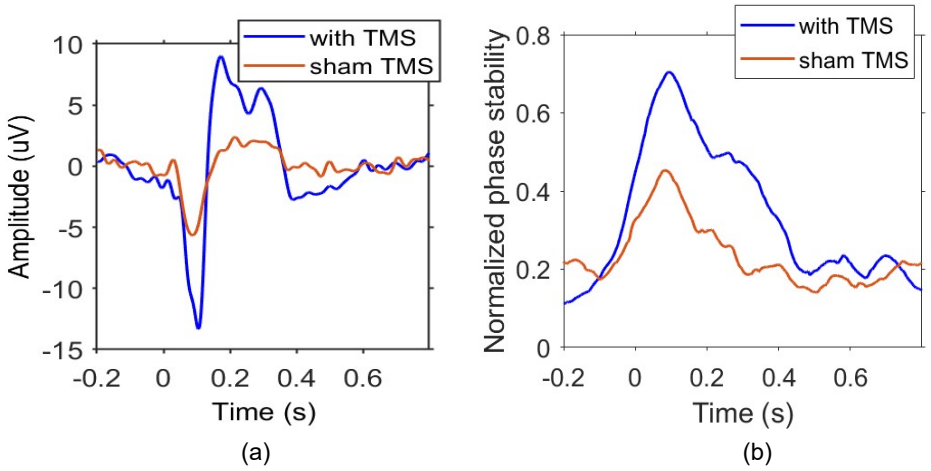


Figure 7: (a) Averaged evoked responses of TEP+AEP compared to sham TMS+AEP (AEP without TMS) for ten subjects. (b) Averaged phase synchronization stability of TEP+AEP compared to sham TMS+AEP (AEP without TMS) for ten subjects.

Latency of TMS Effect to AEP

Figure 8 shows the averaged of the AEPs with TMS influence compared to AEPs with sham TMS through all subjects for 1 second, 2 seconds and 3 seconds after TMS. From these average AEPs, there are no significant differences between AEPs with TMS and AEPs with sham TMS compared to the TEP differences in Figure 7.

As for the AEPs after 1 second of TMS in Figure 8(a), the averaging of the AEPs did not show any observable difference in N100 waves (negative potentials at 100ms after auditory stimulation) with ANOVA p=0.11. This happens because some of the waves in the ERPs without TMS are very high and some are too small, but they cancel each other out and become similar to the AEPs with TMS. This is the reason that we cannot rely totally on the averaging method especially with small number of subjects, epochs or elements with high variation. However, a slight difference in the P200 (positive potentials at 200ms after auditory stimulation) and P300 (positive potentials at 300ms after auditory stimulation) can be observed between the two AEPs.

After 2 seconds of TMS and sham TMS, the averaged AEPs reveal a slight difference in the N100 and P200 waves with ANOVA p=0.08 as shown in Figure 8(b). The AEP with sham TMS shows greater negativity in the N100 wave, while the AEP with TMS demonstrates greater positivity in the P200 wave. It is possible that TMS suppresses the N100 component while not affecting the P200 component. TMS can modulate neural activity in specific ways, depending on the parameters used (e.g., intensity, frequency). The N100 wave is typically associated with sensory processing and attention mechanisms. TMS might suppress this wave by altering the excitability of neurons involved in these processes. On the other hand, the P200 wave is linked to higher-order cognitive processes and might not be as directly influenced by TMS under certain conditions.

In contrast, the AEPs 3 seconds after stimulation show no significant difference between TMS and sham TMS with ANOVA p=0.12 as illustrated in Figure 8(c). This observation suggests that the effects of TMS on the AEPs might be transient, primarily influencing the early components like the N100 and P200 waves but not persisting into the later components. This could indicate that TMS impacts the immediate neural response to auditory stimuli but does not have a long-lasting effect on the AEPs observed after 3 seconds interval.

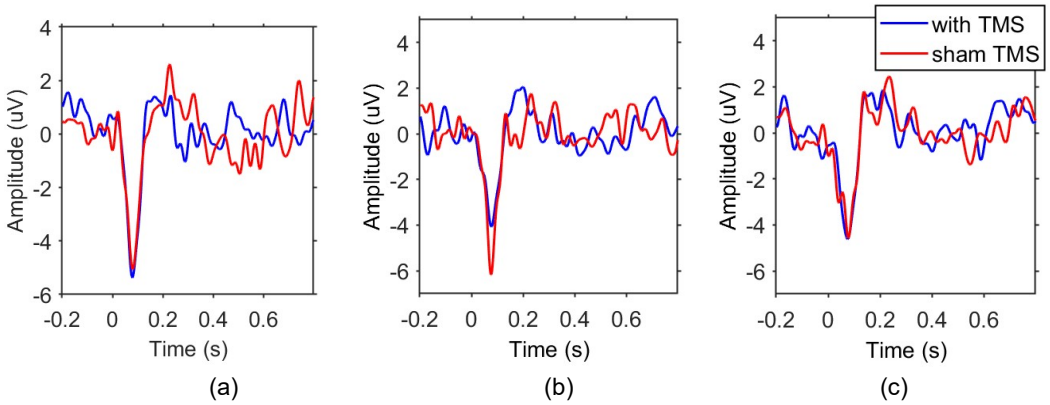


Figure 8. Averaged AEPs with TMS influence compared to AEPs with sham TMS through all subjects for (a) 1 second after TMS, (b) 2 seconds after TMS and (c) 3 seconds after TMS

Figure 9 illustrates the phase synchronization stability measures of the AEPs at three time points (1, 2, and 3 seconds) following both TMS and sham TMS. Data was averaged across all study participants. The leftmost, middle, and rightmost figures correspond to 1-, 2-, and 3-seconds post-stimulation, respectively. Here, the phase stability of the AEP after 1 second of TMS is significantly higher at N100 waves in comparison to sham TMS followed by P200 and P300 waves with ANOVA p=0.01. Thus, the hidden discriminant information which is the phase synchronization of the signals can be highlighted even though the averaging of the AEPs did not show a significant difference. Furthermore, the phase stability of AEP after 2 seconds of TMS is a bit lower than the sham TMS with ANOVA p=0.30. Meanwhile, the phase stability of AEPs after 3 seconds of TMS did not show any significant difference with ANOVA p=0.53.

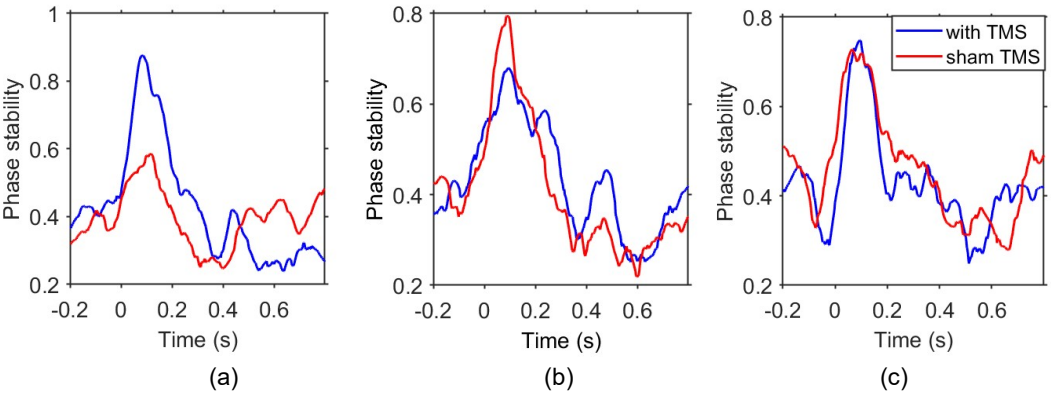


Figure 9: Phase synchronization stability of AEPs with TMS influence compared to AEPs with sham TMS through all subjects for (a) 1 second after TMS, (b) 2 seconds after TMS and (c) 3 seconds after TMS

Table 1 summarizes the results of an ANOVA-based comparison between auditory evoked potentials (AEPs) recorded following real transcranial magnetic stimulation (TMS) versus sham TMS across all subjects. The analysis was performed for three post-TMS time windows—1, 2, and 3 seconds—using two signal extraction methods: Averaging and Phase Stability. The values represent p-values from the ANOVA, indicating the statistical significance of differences between real and sham TMS conditions. For the Averaging method, p-values remain above the typical significance threshold (0.05) across all time windows (0.11, 0.08, and 0.12), suggesting no statistically significant effect of TMS on AEPs using this method. In contrast, the Phase Stability method reveals a highly significant difference at 1 second post-TMS ($p = 0.01$), with reduced but still notable significance at 2 and 3 seconds ($p = 0.30$ and 0.53, respectively). These findings indicate that the Phase Stability method is more sensitive to TMS-induced changes in brain activity, particularly within the first second after stimulation, while Averaging may obscure subtle neural effects.

Table 1. ANOVA significant test of AEPs with TMS influence compared to AEPs with sham TMS through all subjects for 1, 2 and 3 seconds after TMS with both averaging and phase stability methods

Method	AEP 1s	AEP 2s	AEP 2s
Averaging	0.11	0.08	0.12
Phase stability	0.01	0.30	0.53

Although few studies have directly investigated the latency effects of TMS on AEPs, comparisons were made with related studies examining TEPs and sensory cortex modulation. AEPs are critical components in the study of brain responses to auditory stimuli, particularly in the context of TMS combined with EEG. The TMS pulse generates a loud clicking sound that can elicit AEPs, complicating the interpretation of TMS-EEG data. This is because the auditory stimuli can produce responses that overlap temporally with the TEPs, leading to potential confounding factors in the analysis of cortical excitability and connectivity [20].

Research has also indicated that the timing of auditory stimuli relative to TMS can significantly influence the observed AEPs. For example, auditory stimuli presented shortly after TMS can evoke mid-latency peaks in AEPs, which may obscure the interpretation of TEPs [23]. This temporal overlap necessitates careful experimental design to ensure that the contributions of auditory stimuli are adequately controlled. Furthermore, the potential for AEPs to dominate the TEP recordings underscores the importance of developing robust methodologies for artifact rejection and signal separation in TMS-EEG studies [25].

The implications of AEPs in TMS-EEG research extend to clinical applications, where understanding the interplay between auditory processing and cortical excitability can inform treatment strategies for various neuropsychiatric conditions. For instance, alterations in AEPs can be indicative of central auditory processing disorders, which may co-occur with other neurological conditions [26]. Thus, integrating AEP analysis within TMS-EEG frameworks can provide valuable insights into the neural mechanisms underlying auditory perception and its relationship with motor and cognitive functions [29].

Conclusions

In conclusion, the application of Transcranial Magnetic Stimulation (TMS) appears to have a transient impact on the auditory evoked potentials (AEPs), primarily influencing the early components such as the N100 and P200 waves. Specifically, AEPs with sham TMS show greater negativity in the N100 wave, while AEPs with TMS exhibit greater positivity in the P200 wave. These effects are observed within the first second after stimulation. However, AEPs recorded at 2- and 3-second intervals post-stimulation show no significant differences between TMS and sham TMS, suggesting that the influence of TMS diminishes over time. This indicates that TMS may modulate neural activity immediately following stimulation, but this modulation does not persist into later time points.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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