

Applications of Transcranial Alternating Current Stimulation in Psychological Research

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Abstract

Transcranial alternating current stimulation (tACS) is a non-invasive electrical neuromodulation technique that delivers periodic microcurrents of specific frequencies to the scalp to modulate neural oscillations in particular brain regions, thereby altering specific cognitive functions or ameliorating clinical symptoms. Since 2008, psychology researchers have employed tACS to uncover causal relationships between distinct neural oscillatory frequency bands and specific cognitive activities. We first introduce the mechanism by which tACS modulates neural oscillations, followed by a discussion of its applications in research on modifying single-brain and dual-brain cognitive functions. Future studies must precisely control the phase relationship between tACS-delivered currents and the brain's spontaneous EEG rhythms, account for individual differences in neural rhythmicity, and achieve precise tACS neuromodulation to better elucidate the neural electrical mechanisms underlying various cognitive functions. Additionally, systematic evaluation of treatment protocols and therapeutic durability in clinical application research is required to provide scientific guidance for clinical practice.

Full Text

Applications of Transcranial Alternating Current Stimulation in Psychological Research

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Abstract

Transcranial alternating current stimulation (tACS) is a non-invasive neuromodulation technique that modulates neural oscillations in specific brain regions

by applying periodic, low-intensity electrical currents at defined frequencies to the scalp, thereby altering specific cognitive functions or ameliorating clinical symptoms. Since 2008, psychological researchers have employed tACS to reveal causal relationships between distinct neural oscillation frequencies and particular cognitive activities. This review first introduces the mechanisms through which tACS modulates neural oscillations, then systematically examines its applications in modulating both single-brain and dual-brain cognitive functions. Future research should precisely control the phase relationship between applied currents and endogenous brain rhythms, account for individual differences in neural oscillations, and achieve precise tACS neuromodulation to better elucidate the electrophysiological mechanisms underlying various cognitive functions. Simultaneously, systematic evaluation of treatment protocols and the durability of therapeutic effects in clinical applications is needed to provide scientific guidance for clinical practice.

Keywords: transcranial electrical stimulation, transcranial alternating current stimulation, brain oscillations, cognitive function, emotion regulation, clinical treatment

1. Introduction

Transcranial electrical stimulation (tES) is a non-invasive brain stimulation technique that regulates neural activity synchrony and excitability by delivering low-intensity currents to target brain regions, primarily encompassing three modalities: transcranial random noise stimulation (tRNS), transcranial direct current stimulation (tDCS), and transcranial alternating current stimulation (tACS) [?, ?, ?, ?, ?]. Among these, tRNS enhances neuroplasticity through random noise electrical signals [?, ?], while tDCS utilizes constant low-intensity direct current to alter cortical excitability—typically, anodal stimulation induces neuronal depolarization to enhance excitability, whereas cathodal stimulation hyperpolarizes neurons to suppress cortical activity (see review: Liu et al., 2021). In contrast, tACS delivers periodic sinusoidal alternating currents through the scalp and skull to the cerebral cortex, enabling frequency-specific modulation of neural oscillations [?, ?, ?]. Unlike tDCS research that primarily focuses on “where information is processed,” tACS investigations emphasize “how information is dynamically processed,” with the core approach being the modulation of specific neural oscillation frequencies in terms of power or phase. Due to its resonance characteristics with endogenous brain rhythms, tACS has become a unique tool for investigating the causal mechanisms of neural oscillations and inter-brain synchrony in cognitive functions [?, ?, ?, ?, ?]. Furthermore, as a novel tACS modality, temporal interference (TI) stimulation achieves focused modulation of deep brain regions (e.g., hippocampus) by superimposing two (or more) high-frequency alternating currents with slightly different frequencies to generate low-frequency envelope signals within specific brain areas [?, ?]. In recent years, TI stimulation has been preliminarily applied in motor control [?, ?, ?], spatial navigation [?, ?], and working memory [?, ?], demonstrating

promising translational potential for clinical applications.

The mechanisms of tACS offer multiple advantages. First, by applying sinusoidal alternating currents that match endogenous brain oscillation frequencies, tACS can modulate the phase synchrony and amplitude power of neuronal ensembles [?, ?]. Second, tACS can leverage phase characteristics to deliver in-phase (0° phase difference) or anti-phase (180° phase difference) stimulation across different brain regions, thereby modulating inter-brain neural synchrony at specific frequency bands [?, ?] and causally revealing the critical role of dual-brain neural rhythm coupling in social interaction [?, ?, ?, ?]. Moreover, tACS applications across different age groups have shown no side effects, with minimal pain perception and silent device operation [?, ?], ensuring excellent safety and broad applicability.

Given these unique advantages in neuromodulation, tACS demonstrates tremendous potential in psychological research. This review first elucidates the mechanisms of tACS, then summarizes findings from various cognitive domains, outlines key stimulation parameters, and finally prospects future applications, particularly its potential value in enhancing cognitive function and treating psychiatric disorders. The literature search for this review was conducted as follows: As of June 2025, 33 studies investigating tACS applications in perception, attention, motor control, learning and memory, emotion regulation, and interpersonal interaction were identified in PubMed and Web of Science. Technical search terms included: tACS, transcranial alternating current stimulation, hyper-tACS, dual-tACS, temporal interference stimulation; cognitive search terms included: perception, pain, attention, motion, learning, memory, emotion regulation, social interaction.

2. Mechanisms of tACS

The primary mechanism of tACS involves neural synchronization. By delivering alternating currents at specific frequencies, tACS induces phase alignment of neural oscillations in target brain regions. This phase-dependent modulation triggers rhythmic fluctuations in presynaptic neuronal membrane potentials, thereby enhancing synaptic plasticity and achieving dynamic regulation of cortical excitability [?, ?]. Specifically, its mechanisms encompass three levels: local neural oscillation regulation, brain network connectivity optimization, and neuroplasticity enhancement.

At the local neural oscillation regulation level, tACS induces synchronization between endogenous and exogenous currents by delivering alternating currents that match the intrinsic rhythms of target brain regions. This neural entrainment phenomenon enhances rhythmic synchronous activity of local neuronal ensembles, thereby improving information encoding efficiency [?, ?]. For example, researchers applied 1 mA alpha-tACS to participants' occipital cortex (Oz) and found significantly enhanced alpha oscillation power in visual cortex, which subsequently optimized performance on visual attention tasks [?, ?].

At the brain network optimization level, tACS modulates endogenous neural oscillation synchrony and coupling characteristics by delivering alternating currents with adjustable phase differences across brain regions [?, ?], including frequency-specific synchronization and cross-frequency phase-amplitude coupling. Regarding frequency-specific synchronization, tACS enhances phase consistency within neuronal clusters at the same frequency band (e.g., theta or gamma), optimizing inter-regional information integration efficiency [?, ?]. In terms of cross-frequency phase-amplitude coupling, when high-frequency activity in presynaptic neurons (e.g., gamma-band burst firing) precisely aligns in time with low-frequency oscillation phases in postsynaptic neurons (e.g., theta-band depolarization phases), it can activate timing-dependent plasticity. This process ensures optimal synchronization between pre- and postsynaptic potential changes when excitability peaks, further enhancing directional information transfer efficiency between brain regions [?, ?]. For instance, researchers applied 2 mA in-phase delta-beta cross-frequency tACS or theta-gamma cross-frequency tACS to participants' prefrontal cortex (F4) and motor cortex (C4), finding that delta-beta coupling was significantly enhanced during rule abstraction tasks related to action selection, whereas theta-gamma coupling was enhanced during rule-number tasks related to working memory [?, ?]. This result provides causal evidence that prefrontal cortex regulates motor and memory functions through different cross-frequency couplings. Additionally, tACS can modulate multi-scale brain network connectivity through rhythmic external electric fields, including short-range intrahemispheric connections, long-range interhemispheric connections [?, ?, ?], and even whole-brain topological network reorganization [?, ?]. These multi-level effects demonstrate that tACS not only enhances directional information flow through frequency-specific synchronization but also flexibly adapts to complex cognitive processing demands through cross-frequency coupling and network reorganization.

Finally, at the neuroplasticity enhancement level, tACS effects depend on the activation of synaptic plasticity and can persist for minutes to hours after stimulation cessation. Studies have found that applying 2 mA beta-tACS to primary motor cortex can significantly increase motor evoked potential amplitudes by activating N-methyl-D-aspartate (NMDA) receptor-mediated long-term potentiation. However, this effect is completely blocked when NMDA receptor antagonists are administered [?, ?]. This indicates that tACS periodic currents trigger synaptic remodeling through calcium-dependent signaling pathways [?, ?], thus holding promise for achieving long-term functional changes in neural circuits.

3. tACS Modulation of Single-Person Cognitive Functions

Neural oscillations constitute the core mechanism of brain information encoding. Different frequency bands coordinate neuronal population activity to achieve efficient information transmission and integration [?, ?]. Based on oscillation frequency, neural activity is typically divided into five bands: delta (0.5–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (13–30 Hz), and gamma (>30 Hz). Dif-

ferent frequency bands are closely associated with specific mental states or cognitive functions. Theta oscillations are implicated in working memory, spatial navigation, learning [?, ?], and emotion regulation [?, ?]. Alpha oscillations are widely associated with attention allocation, perception, and cognitive control [?, ?, ?]. Beta oscillations are primarily related to motor control [?, ?], while gamma oscillations participate in higher-order cognitive functions such as memory updating and emotional processing [?, ?, ?]. These findings provide a theoretical foundation for selecting appropriate tACS frequencies.

By modulating neural oscillations at specific frequencies, tACS influences the synchronization and coupling states of functional brain networks, thereby achieving regulation of diverse cognitive functions. This frequency-specific modulation mechanism offers new perspectives for revealing the neural basis of cognitive processes and exploring interventions for psychiatric and neurological disorders. Existing research indicates that different tACS frequencies demonstrate relatively dissociated targeting effects: alpha primarily affects perceptual processing and spatial attention, beta facilitates motor control, while theta and gamma play important roles in learning/memory and emotion regulation. This section systematically summarizes findings on different frequency tACS applications across cognitive domains and discusses their translational value in clinical practice.

3.1 Perception tACS can effectively alter perceptual experiences by modulating alpha neural oscillations, such as enhancing visual sensitivity, improving auditory hallucination symptoms, or modulating pain perception [?, ?, ?, ?].

In the visual domain, a recent study [?, ?] simultaneously stimulated participants' frontal (Fz) and occipital (Oz) regions with 0.37 mA alpha-tACS while manipulating the phase difference between the two brain regions using 45° (frontal leading occipital by 45°) and -45° (frontal lagging occipital by 45°) conditions. In a visual detection task requiring participants to judge whether faint stimuli appeared in the visual field, the 45° condition not only significantly enhanced neural oscillations from frontal to occipital cortex (i.e., backward traveling waves) but also reduced visual contrast thresholds. This study reveals the causal role of alpha neural transmission pathways from frontal to occipital regions in visual perception.

In the auditory domain, clinical studies on schizophrenia patients with auditory hallucinations have employed 2 mA in-phase alpha-tACS to the left dorsolateral prefrontal cortex (F3/FP1) and temporoparietal junction (T3/P3), finding that this intervention significantly improved hallucination symptoms while enhancing spontaneous alpha-frequency EEG oscillations and 40 Hz auditory steady-state evoked responses [?, ?, ?, ?].

Regarding pain perception, researchers have discovered that alpha oscillation power changes are associated with membrane gating mechanisms. When alpha oscillations are enhanced, increased synchrony between cortical and subcortical regions may inhibit ascending sensory information transmission, thereby

reducing pain signal perception [?, ?]. Based on this, studies applying 1 mA alpha-tACS to bilateral somatosensory cortex (CP3 and CP4) found reduced subjective perception of mechanical pressure pain accompanied by significantly decreased unpleasantness ratings [?, ?]. Other research combining fMRI further explored alpha-tACS effects, demonstrating that 1 mA tACS applied to primary motor cortex (C3/C4) effectively reduced subjective experience of acute laser-induced thermal pain. Post-stimulation, bilateral sensorimotor cortex activation was significantly attenuated, and functional connectivity with pain-related regions including anterior cingulate cortex, insula, and prefrontal cortex was reduced [?, ?]. Recent studies applying 1.5 mA alpha-tACS to primary motor cortex (C4) or dorsolateral prefrontal cortex (F3) also found reduced persistent pain induced by capsaicin [?, ?, ?]. However, some studies have failed to observe alpha-tACS effects on pain perception. For example, researchers applied 1 mA alpha-tACS or gamma-tACS to somatosensory cortex (CP3 and CP4) and dorsolateral prefrontal cortex (F3 and F4), but found no modulation of persistent thermal pain induced by thermodes [?, ?]. These discrepant results may be attributable to differences in pain types, tACS application sites, and participant states across experiments. Future research should accumulate further empirical evidence to better understand tACS mechanisms in pain modulation and provide guidance for clinical applications.

3.2 Attention Parietal alpha neural oscillations are associated with spatial attentional inhibition. Numerous studies indicate that alpha-tACS can alter spatial attention, particularly top-down endogenous attention [?, ?, ?]. In visuospatial attention tasks, when participants attend to the left visual field, alpha power decreases in the right parietal hemisphere while increasing in the left hemisphere. This pattern aligns with the contralateral processing characteristic of visual pathways (left visual field input processed by right hemisphere), suggesting that visual attention activates ipsilateral regions while suppressing contralateral alpha power [?, ?]. Based on this, one study applied 2 mA alpha-tACS to participants' left parietal cortex (P3) to suppress left parietal attentional function, finding that participants showed longer reaction times for right visual field targets than left visual field targets, indicating that alpha-tACS impaired right visual field spatial attention capacity [?, ?]. This finding has been supported by subsequent studies confirming that alpha-tACS plays a causal role in visuospatial attention within the parietal-based dorsal attention network, manifesting as suppression of contralateral visual field attention [?, ?, ?].

Beyond visuospatial attention, tACS also affects auditory spatial attention but shows no significant effects on non-spatial attention. Given that auditory pathways also exhibit contralateral processing advantages [?, ?], applying 1.5 mA alpha-tACS to participants' right parietal cortex (P2) significantly disrupted auditory spatial attention to left-side sounds but did not affect non-spatial attention tasks requiring gender discrimination [?, ?]. Similarly, another study applying 2 mA alpha-tACS to parieto-occipital cortex (Cz and Oz) found no effect on non-spatial attention tasks requiring temporal discrimination [?, ?].

Additionally, recent research has investigated the neural mechanisms of visual crowding (peripheral interference with central target perception) [?, ?]. Using 1.6 mA alpha or beta-tACS over right parietal cortex (P4), the study found that beta-tACS, but not alpha-tACS, improved visual discrimination ability and significantly reduced visual crowding effects. This represents the only evidence to date of non-alpha-tACS effects in the perception domain.

3.3 Motor Control Beta neural oscillations are intimately related to motor control [?, ?]. A meta-analysis demonstrated that beta-tACS applied to primary motor cortex enhances corticospinal tract excitability and improves central nervous system control of limbs and trunk [?, ?], providing important reference for clinical intervention in neurodegenerative disorders such as Parkinson's disease [?, ?, ?]. For example, in finger-tapping tasks, researchers applied 1 mA beta-tACS to Parkinson's patients' primary motor cortex, finding that beta-tACS significantly alleviated bradykinesia compared to sham stimulation [?, ?, ?]. A recent study simultaneously examined tDCS and beta-tACS interventions for Parkinson's symptoms and their neural mechanisms, finding that 2 mA stimulation of primary motor cortex (C3) reduced abnormal beta power discharge and improved bradykinesia regardless of current type. However, beta-tACS more significantly modulated beta oscillations and showed more immediate improvement in motor flexibility compared to tDCS [?, ?]. This suggests both techniques improve motor symptoms but through different mechanisms: tDCS likely modulates beta oscillations indirectly by altering cortical excitability, whereas tACS directly intervenes in abnormal beta synchronization. Furthermore, researchers applied 1.8 mA tACS targeting beta-gamma cross-frequency coupling to bilateral orbitofrontal cortex in obsessive-compulsive disorder patients, finding improved control behaviors (including compulsive action control) with therapeutic effects lasting up to 3 months after 5 consecutive days of 30-minute interventions [?, ?]. In summary, beta-tACS applied to primary motor cortex can directly modulate abnormal neural oscillations, holding important clinical value for improving motor control.

3.4 Learning and Memory Theta and gamma neural oscillations play crucial roles in learning and memory. Meta-analyses indicate that tACS at these frequencies shows brain region-specific effects on memory: theta-tACS applied to temporoparietal regions significantly affects working memory, while gamma-tACS applied to prefrontal cortex effectively influences long-term memory [?, ?, ?]. Reinhart and Nguyen (2019) used an object change detection task to apply 1.6 mA in-phase theta-tACS (0.6 mA to left prefrontal cortex and 1 mA to temporal cortex) in older adults, finding that this manipulation enhanced both frontotemporal theta phase synchronization and theta-gamma cross-frequency coupling, accompanied by improved working memory accuracy. Subsequently, this research group applied 1.58 mA theta-tACS and gamma-tACS to dorsolateral prefrontal cortex (AF3) and inferior parietal lobule (CP5) respectively in older adults during free recall tasks, discovering that theta-tACS targeting

the inferior parietal lobule improved working memory, whereas gamma-tACS targeting dorsolateral prefrontal cortex optimized long-term memory [?, ?]. Additionally, recent studies found that 5 Hz TI stimulation targeting the hippocampus significantly improved episodic memory accuracy [?, ?], revealing the hippocampus' s central role in episodic memory. Other research examining TI effects on working memory in 3-back tasks found that 6 Hz TI targeting middle frontal gyrus (F4) and inferior parietal lobule (P4) effectively improved working memory performance [?, ?]. Furthermore, TI can modulate deep brain regions through cross-frequency coupling mechanisms to influence working memory, though this technique' s effectiveness requires further empirical validation [?, ?]. Beyond memory, theta-tACS has also been shown to facilitate learning. In arithmetic learning tasks, researchers applied 1 mA theta-tACS to dorsolateral prefrontal cortex (F3) or posterior parietal cortex (P3), finding that theta-tACS over dorsolateral prefrontal cortex, compared to posterior parietal cortex, improved learning efficiency for new rules [?, ?].

In clinical populations, gamma-tACS has been found to improve episodic memory in Alzheimer' s disease patients, manifested as more accurate long-term memory, an effect observed in both murine and human studies [?, ?, ?]. For example, researchers applied 135 A gamma-tACS to the right hippocampus of memory-impaired mice for 21 consecutive days, finding that compared to sham stimulation, the experimental group showed significantly improved accuracy in Y-maze tasks and enhanced functional connectivity from right hippocampus to prefrontal cortex [?, ?]. In Alzheimer' s patients, 3 mA gamma-tACS applied to parietal cortex (Pz) improved immediate and delayed recall performance in episodic memory tasks and enhanced associative memory scores compared to control groups [?, ?].

In summary, theta and gamma frequency tACS play important roles in learning and memory processes. Theta-tACS primarily modulates working memory and learning capacity, while gamma-tACS facilitates long-term memory consolidation and shows application potential for improving episodic memory in Alzheimer' s disease patients.

3.5 Emotion Regulation tACS influences emotion regulation capacity and emotional experience by modulating neural synchrony across different brain regions or cross-frequency phase-amplitude coupling. Given the prefrontal cortex' s central role in emotion regulation, this region represents the primary target for tACS studies [?, ?]. Bramson et al. (2020) applied 2 mA in-phase theta and gamma tACS to participants' right prefrontal cortex and left sensorimotor cortex, promoting cross-frequency phase-amplitude coupling between these regions at theta and gamma frequencies. This enhanced behavioral control in emotional approach-avoidance tasks and reduced error rates. fMRI revealed that these improvements were associated with enhanced prefrontal inhibition of sensorimotor cortex, providing neuro-mechanistic evidence for tACS in ameliorating social emotional disorders such as social anxiety. Tang et al. (2025)

applied 1.5 mA in-phase theta-tACS to dorsolateral prefrontal cortex (F3) and ventrolateral prefrontal cortex (F8), enhancing neural synchrony between these regions and thereby improving participants' ability to down-regulate negative emotions using cognitive reappraisal strategies. This study demonstrates that both dorsolateral and ventrolateral prefrontal cortex are causal brain regions for emotion regulation that require synchronized activity (rather than the 180° phase difference in control conditions) to successfully complete emotion regulation tasks.

In clinical research, excessive theta-frequency synchronization in cerebral cortex is considered an important biomarker for depression and anxiety disorders [?, ?]. Based on this finding, one study measured the two electrode locations with strongest theta power in internalizing psychopathology patients at rest and applied anti-phase 1.5 mA theta-tACS, finding significant improvements in emotion regulation performance and symptom alleviation [?, ?]. This study also found that theta-tACS intervention at two target sites showed greater advantages in enhancing emotion regulation capacity and promoting symptom improvement compared to tDCS applied to left dorsolateral prefrontal cortex. Beyond theta frequency, tACS targeting alpha and gamma frequencies can also improve major depressive symptoms. For instance, studies found that 15 mA 77.5 Hz gamma-tACS applied to prefrontal cortex (FPz, FP1, FP2) for 2–4 weeks significantly improved depressive symptoms [?, ?, ?], while 2 mA alpha-tACS applied to prefrontal cortex (F3, F4, Cz) also effectively alleviated symptoms [?, ?, ?].

The mechanisms of alpha-tACS in these clinical studies may involve modulation of abnormally enhanced alpha activity in prefrontal cortex of depressed patients, which may reflect cortical over-inhibition closely related to anhedonia [?, ?]. Gamma-tACS mechanisms may involve high-frequency stimulation modulating endorphin and other neurotransmitter levels in cerebral cortex, with these neurochemical changes considered important biological mechanisms for alleviating depressive symptoms [?, ?, ?]. Current understanding of intervention mechanisms for gamma- versus alpha-tACS in depression remains inconclusive, and it is unclear whether tACS improves emotion regulation capacity, emotional experience, or other related functions. Future research should further investigate these mechanisms.

In summary, tACS plays an important role in improving emotion regulation capacity, particularly in depression treatment, by modulating neural oscillations at different frequencies (theta, alpha, gamma). However, the intervention mechanisms and therapeutic effects of different tACS frequencies require further exploration.

4. tACS Applications in Interpersonal Interaction

In social interaction research, hyperscanning techniques have revealed neural synchronization between interacting brains. Regarding the mechanisms of inter-

brain synchronization, some scholars argue that it represents a specific social state actively formed by individuals for efficient interactive communication, similar to intra-brain regional cooperation mechanisms [?, ?], while others suggest it may merely reflect concomitant brain synchronization from shared sensory input or similar behaviors [?, ?]. However, hyperscanning only provides correlational evidence, making it difficult to prove or refute these theoretical perspectives. Subsequent research can utilize inter-brain neuromodulation techniques like tACS to manipulate inter-brain neural activity synchrony, thereby revealing its causal role in interpersonal interaction.

Novembre et al. (2017) pioneered inter-brain tACS technology by applying 1 mA tACS to left primary motor cortex (C3) in two participants to explore its effects on interpersonal synchronization behavior. Participants were required to maintain rhythmically consistent button-pressing with their partner. Results showed that only 20 Hz in-phase tACS significantly enhanced movement rhythm synchrony in paired participants, while anti-phase stimulation and 2 Hz or 10 Hz conditions showed no such effects. This study demonstrated that synchronized beta oscillations in bilateral motor cortices effectively facilitate behavioral coordination. Similarly, a recent study applying 1.5 mA 20 Hz in-phase tACS to right inferior frontal gyrus (FC6) in each pair of participants improved success rates in cooperative button-pressing tasks, with tACS more significantly enhancing prefrontal inter-brain synchrony compared to tDCS [?, ?].

Previous studies have shown that frontal theta oscillations are crucial for individual learning and memory [?, ?, ?]. Based on this, Pan et al. (2021) applied 1 mA tACS to left inferior frontal gyrus (FC5) in both instructors and learners during music learning tasks, finding that 6 Hz in-phase tACS induced spontaneous body movement synchrony between participants and significantly improved learners' music task performance, whereas 6 Hz anti-phase or 10 Hz in-phase tACS conditions produced no such effects. Further analysis revealed positive correlations between body movement synchrony and music learning improvement.

Applying in-phase tACS to specific brain regions not only promotes interpersonal synchronization behavior but also enhances mutual intention understanding in social interactions. For example, in a communication task using meaningless symbols, researchers applied 1 mA 40 Hz in-phase tACS to bilateral temporoparietal junctions (CP5) in dual brains, finding that successful concept alignment groups showed significantly higher gamma-frequency phase-locking values between left temporoparietal junction and occipital regions compared to unsuccessful groups. tACS enhanced communication accuracy in successful concept alignment groups but had no effect on unsuccessful groups [?, ?]. Subsequently, this research group further investigated the dynamic process of establishing communication systems through encoding multiple symbol systems (shapes, colors, letters, etc.) [?, ?], finding that successful symbol system establishment groups showed higher inter-brain synchrony in right superior temporal gyrus (CP6) than failure groups. Importantly, compared to sham and anti-phase tACS, in-phase gamma-tACS significantly enhanced superior temporal

gyrus inter-brain synchrony and consequently improved success rates in interpersonal symbol system establishment. These results suggest that promoting neural synchrony in bilateral temporoparietal regions through gamma-tACS supports social communication and collaborative construction of complex symbol systems.

In summary, tACS can effectively promote interpersonal cooperation, intention understanding, and social learning by enhancing inter-brain neural activity synchrony.

5. Optimization of Key tACS Parameters

tACS modulation effects depend on optimization of key parameters including current intensity, stimulation duration, electrode configuration, and phase relationships. Based on the aforementioned research, this section systematically analyzes optimization strategies for these parameters to enhance tACS efficacy in cognitive function modulation and interpersonal interaction, providing theoretical and practical guidance for future studies.

(1) Current Intensity: Some researchers argue that low-intensity stimulation below 2 mA is insufficient to effectively alter neuronal firing activity [?, ?]. However, excessively high intensity may cause discomfort such as scalp burning, tingling, or itching [?, ?]. Literature review indicates that current basic research typically employs 1-2 mA to effectively influence behavior and brain activity patterns. Clinical studies often use 2-4 mA, with some studies attempting 15 mA to enable current delivery to deep brain regions such as hippocampus and amygdala [?, ?, ?].

(2) Stimulation Duration: Duration varies by research objective. Studies focusing on offline effects examine sustained cognitive changes after stimulation, typically using single sessions of 20 minutes [?, ?, ?, ?]. Online effect studies assess cognitive performance during stimulation, often employing rapid task condition switching (1 to several minutes per condition) with shorter single-session durations (minimum 1 minute) to observe real-time tACS modulation [?, ?, ?, ?]. Notably, 1-minute tACS is sufficient to induce changes in behavior and brain activity patterns. Clinical interventions often use repeated stimulation protocols (20-40 minutes daily for 10-20 days) to consolidate effects, though evidence for long-term effects remains limited [?, ?, ?, ?].

(3) Electrode Configuration: Conventional tACS uses two 25-35 cm² electrodes (stimulation and return electrodes) to deliver current to the scalp [?, ?, ?]. For example, in the first study using tACS to modulate human endogenous neural oscillations, Antal et al. (2008) placed the stimulation electrode over left motor cortex (16 cm²) and the return electrode over right orbitofrontal cortex (50 cm²), using asymmetric dual-electrode configuration with enlarged return electrode area to enhance current density in the target region. To address the weak focality of conventional electrodes, researchers have proposed ring-return electrode configurations using a central stimulation electrode with a ring-shaped

return electrode or multiple small surrounding return electrodes to achieve focused current density enhancement in targeted areas, improving stimulation precision and focality [?, ?, ?, ?]. In conventional electrode configurations for dorsolateral prefrontal cortex stimulation, the stimulation electrode is typically placed at F3 with the return electrode on the ipsilateral shoulder [?, ?]. In ring electrode configurations, a central stimulation electrode at F3 is combined with four small return electrodes (F1, AF3, FC3, F5) [?, ?]. Additionally, researchers have introduced electric field modeling techniques using finite element or boundary element methods to simulate current distribution across scalp, skull, and brain tissue, thereby precisely predicting electric field strength and focality in target regions [?, ?]. It should be noted that unlike conventional tACS electrode configurations, TI stimulation requires at least two pairs of electrodes on the scalp to generate two high-frequency alternating currents that form low-frequency interference currents within the brain [?, ?].

(4) Phase Relationship: Phase relationship refers to the synchrony between applied current and endogenous EEG rhythms or phase consistency across multiple brain regions and individuals. Current research predominantly employs in-phase stimulation (including same-frequency or cross-frequency) to enhance inter-regional communication efficiency and improve cognitive task performance such as working memory and attention [?, ?, ?, ?]. In-phase stimulation also effectively enhances inter-brain synchrony and improves interpersonal cooperation and communication [?, ?, ?, ?]. Anti-phase stimulation reduces communication efficiency, inhibits specific cognitive functions, or is used to modulate abnormal synchronization in patients with depression or anxiety [?, ?, ?, ?]. Additionally, specific phase differences (e.g., 45°) can simulate natural dynamic phase relationships between brain regions, such as frontal cortex phase-leading occipital cortex during visual perception [?, ?].

6. Summary and Outlook

Since Antal et al. (2008) first applied tACS technology to modulate human endogenous neural oscillations, tACS has become an important tool in psychological research for investigating causal relationships between neural oscillations and cognitive processes. This review has summarized tACS applications in psychological research over the past decade, focusing on how tACS causally enhances individual and group performance across multiple cognitive functions by modulating neural oscillation patterns in brain regions, networks, and inter-brain connections (see Tables 1 and 2 in the appendix). In clinical research, tACS demonstrates potential for improving clinical symptoms and restoring cognitive functions by modulating abnormal neural oscillations. However, the field remains in its early developmental stages, with tACS neuromodulation mechanisms not yet fully elucidated and optimal practice protocols (including stimulation parameters and application methods) requiring systematic exploration. Therefore, we propose that future tACS research should advance in three key directions:

First, precise control of phase relationships between applied tACS currents and endogenous brain oscillations is needed. The vast majority of existing tACS studies have not considered phase differences between applied currents and EEG. When phases are misaligned, tACS entrainment effects on spontaneous brain activity may be weakened, reducing intervention efficacy [?, ?]. To achieve precise neuromodulation, real-time monitoring of spontaneous EEG phase is required before and throughout tACS application. However, applied currents superimposed on spontaneous EEG significantly interfere with phase measurement, a technical challenge that has long constrained tACS research development. Recently, researchers have proposed a real-time spatial filtering algorithm—Stimulation Artifact Source Separation (SASS)—that separates stimulation-specific signals from physiological neural oscillations, enabling reliable single-trial EEG amplitude and phase measurement during tACS [?, ?]. Future research should utilize novel algorithms like SASS to: (1) maximize neural entrainment by real-time monitoring and adjusting tACS current phase to maintain optimal phase differences with specific endogenous frequencies, and (2) advance closed-loop regulation system development using adaptive tACS protocols to dynamically modulate specific EEG rhythms.

Second, individual differences must be considered to achieve precise tACS neuromodulation. Regarding stimulation frequency, studies have already highlighted advantages of personalized stimulation frequencies [?, ?, ?, ?]. Regarding stimulation targets, studies have found that individualized target optimization directly enhances tACS modulation effects [?, ?, ?, ?]. For example, in treating depression and anxiety, researchers propose selecting the two brain regions with strongest abnormal connectivity for tACS modulation [?, ?]. Additionally, including control frequencies in studies helps control non-specific tACS effects and validate frequency-specificity, thereby strengthening causal evidence, though most existing studies have not included control frequencies.

Third, systematic evaluation of treatment protocols and therapeutic durability in clinical applications is needed. Although some studies have examined tACS therapeutic durability in depression and Parkinson's patients, follow-up periods have been short [?, ?, ?, ?], which is insufficient for translating immediate intervention effects into long-term therapeutic benefits. To ensure broad clinical application of tACS, future research must investigate the applicability and long-term efficacy of different treatment courses across various disorders.

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