Right frontal gamma transcranial alternating current stimulation modulates optimism biases

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Research Article

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Abstract

Background

When forecasting the future, people often underestimate the likelihood of adverse life events, a phenomenon known as optimism bias. While transcranial alternating current stimulation (tACS) over frontal regions has been employed to modulate various cognitive and emotional functions, its potential impact on optimism bias remains unexplored.

Results

Using a single-blind, sham-controlled, between-subjects design, we investigated the effects of alpha- and gamma-tACS on optimism bias. Three groups of participants received 15-min of either individualized alpha frequency (IAF)-tACS, 40 Hz-tACS, or sham stimulation over the right frontal cortex during rest. To assess how tACS impacted the optimism bias, participants completed a belief update task before and immediately after the tACS. To assess potential delayed effect of the tACS, participants completed a delay estimation task 24 hours later. We found that across all three groups, participants showed the classic optimism bias, such that they were more likely to update their beliefs toward desirable than undesirable feedback. Notably, compared to the sham and IAF-tACS groups, 40 Hz-tACS further enhanced optimism biases after 24 hours.

Conclusion

These findings suggest that right frontal gamma- but not alpha-tACS could effectively modulate the long-term optimistic belief updating. Our study highlights the potential of non-invasive brain stimulation as a promising tool for altering optimism biases, which may benefit individuals with pessimistic outlooks.

Background

Healthy individuals have been shown to exhibit a tendency known as optimism bias, where they are more likely to incorporate positive rather than negative feedback into their belief systems (Garrett & Sharot, 2017; Kuzmanovic et al., 2018; Kuzmanovic & Rigoux, 2017; Sharot et al., 2011; Sharot & Garrett, 2016; Yao et al., 2021). The optimism bias emerges due to the preferential encoding and consolidation of desirable over undesirable information (Garrett et al., 2018; Kuzmanovic et al., 2016, 2018; Sharot et al., 2012; Yao et al., 2021), a process that likely involves frontal brain regions such as the anterior cingulate cortex (ACC) and inferior frontal gyrus (Sharot et al., 2011). Optimism bias plays a crucial role in mental health, with its absence potentially leading to psychiatric disorders like depression, characterized by a reduced inclination to process positive future outcomes (Hobbs et al., 2022; Korn et al., 2014). This link highlights the potential value of cognitive interventions aimed at enhancing optimism bias (Kube, 2023).

Recent developments in non-invasive brain stimulation techniques, especially transcranial alternating current stimulation (tACS), have drawn significant interest for their ability to modulate neural activity and associated behaviors. TACS, which can alter neural oscillations at specific frequencies, has demonstrated efficacy in modifying various cognitive functions in humans (Herrmann et al., 2013; Polanía et al., 2018; Beliaeva et al., 2021; Hartwigsen & Silvanto, 2023; Wischnewski et al., 2023; Grover et al., 2023). In the context of optimism bias, major depressive disorder (MDD) patients exhibit frontal alpha asymmetry (FAA) – a notable difference in alpha power between the brain's right and left hemispheres (Smith et al., 2017). This asymmetry correlates with negative emotional processing involving the amygdala and dorsolateral prefrontal cortex (DLPFC, Zotev et al., 2016). Several tACS studies have used alpha-band stimulation to modulate the frontal alpha power among MDD patients to influence emotional processing, thereby balancing approach and avoidance motivations (Alexander et al., 2019; Riddle et al., 2022).

Additionally, gamma-band activity (30–100 Hz) in the frontal cortex is crucial for cognitive processes such as attention, memory encoding, and executive control (Jensen et al., 2007; Nomura et al., 2019; Grover et al., 2022, 2023). These processes can be essential for the formation of updating of belief systems, including the motivation-dependent optimism bias. Previous studies also suggested a link between reduced gamma-band power and depressive symptoms (T. Y. Liu et al., 2014; Pizzagalli et al., 2006), especially in prefrontal areas (Fitzgerald & Watson, 2018). Thus, modulating gamma oscillations via tACS could enhance the integration of positive information and improve cognitive functions critical for belief updating (Hoy et al., 2015; Manippa et al., 2023; Santarnecchi et al., 2013, 2016). However, whether alpha- and gamma-band tACS can affect optimism biases remains unexplored.

In our study, we administered a single session of high-definition tACS (HD-tACS) to three groups: gamma-tACS, alpha-tACS, and a sham control group, in a frequency-/sham-controlled, single-blind, between-subject design. For alpha-tACS, we applied individualized alpha frequency (IAF) to increase the precision of alpha modulation. For gamma tACS, we used a fixed frequency at 40 Hz. We applied IAF and 40 Hz stimulation over the right prefrontal cortex (F4 region) to influence the neural activity of the right frontal cortex (Alexander et al., 2019; Martínez-Pérez et al., 2022; Riddle et al., 2022). To assess optimism bias, we employed the classic belief update task in which participants would update their estimated probability of experiencing adverse life events in the future (e.g., developing back pain when 60 years old) given desirable and undesirable feedback (Sharot & Garrett, 2016; Garrett et al., 2018; Kuzmanovic et al., 2018; Sharot et al., 2011; Sharot & Garrett, 2022). Optimism biases would be evident if participants preferentially used desirable than undesirable feedback to guide their estimates.

Methods

Participants

Following the sample size in the prior tACS research targeting on prefrontal cortex (Alexander et al., 2019), we aimed to recruit 30 valid participants in each of the three groups (i.e., alpha, gamma and sham groups). To account for potential dropouts and attrition, we recruited a total of 110 participants from a local university. Eligibility was determined through an online pre-screening process, where participant completed the Beck Depression Inventory-II (BDI-II; Beck et al., 1996) and answered questions related to the tACS implementation. To be included in the experiment, participants' BDI-II score should be lower than 29, without current or historical diagnoses of psychiatric disorders, without electronic implants, no history of head injury, and normal or corrected-to-normal vision. Subsequent exclusions were based on the following criteria: suspicion regarding the veracity of feedback probability (n = 7), quit the experiment (n = 3), falling asleep during the stimulation (n = 1), poor EEG data quality (n = 6). After these exclusions, the final sample included 31 participants in the alpha-tACS group (18 males, age: M ± SD = 20.52 ± 1.48), 31 participants in the 40 Hz-tACS group (12 males, age: M ± SD = 20.45 ± 1.48), and 31 participants in the sham control group (16 males, age: M ± SD = 20.66 ± 1.94). Participants received monetary compensation for their time (250 CNY or ~ 36 USD). All participants provided written consent before participation. The Human Research Ethics Committee of Shenzhen University approved the study.

Experimental Design and Task Procedures

Participants visited the lab on two consecutive days. On Day 1, participants completed the baseline belief update task to assess optimism bias, received the tACS, and the post-tACS assessments. After 24 hours, participants came back to the lab for a delay test on Day 2. An overview of the timeline of experimental tasks is illustrated in Fig. 1A.

Day 1 Lab session

Pre-tACS phase: Participants were given task instructions and four practice trials to familiarize with the belief update task. For baseline belief update task, participants completed a total of 48 trials, separated in two blocks with a one-minute break in between. Following baseline optimism bias assessment, 2-minute resting state EEG data were collected to determine each participant's individual alpha frequency (IAF). During the resting-state, participants were instructed to maintain relax and keep their eyes open while fixating on the center of the screen. Individual stimulation intensity was determined during calculation of the IAF.

TACS phase: Subsequent to the determination of IAF and stimulation intensity, the stimulation protocol began, which lasted for approximately 15 minutes (see details below in tACS protocol). During the tACS stimulation, participants completed a modified mental rotation task (Kasten & Herrmann (2017). By engaging in this mental rotation task, we aimed to reduce the individual variances of the brain and cognitive states during the tACS stimulation (Ruhnau et al., 2016).

Post-tACS phase: Following the stimulation, participants spent two minutes for resting-state EEG to calculate the post-stimulation resting FAA. Participants then completed the tACS side-effect questionnaire. Participants next completed the post-tACS belief update task, with a total of 48 trials separated in two blocks.

Additional assessments: A surprise cued recall task was introduced following the post-tACS belief update task. Here, prompted by each adverse life event from the previous belief update task, participants shall recall the feedback probability shown earlier. Similar to Yao et al., (2021), this cued recall task assessed participants' memory accuracy of the feedback. Finally, participants completed three questionnaires to assess trait anxiety (State-Trait Anxiety Inventory, STAI-T; Spielberger, 1983), depression symptoms (Beck Depression Inventory-II, BDI-II; Beck et al., 1996), and trait optimism (Life Orientation Test-Revised, LOT-R; Scheier et al., 1994).

Day Two Lab session

Approximately 24 hours after the Day 1 session, participants returned to the lab for the second lab session on Day 2. They then engaged in the following tasks in order: (1) a surprise belief update task to assess delayed optimism bias; (2) a surprise cued recall task to assess long-term memories for feedback probability; (3) a rating task involving the assessment of adverse life events on a 6-point Likert scale; and (4) additional questionnaires (including the STAI-T, BDI-II, and LOT-R).

Upon completion of all tasks, participants were debriefed and compensated accordingly.

Experimental Tasks

The experimental tasks, implemented in E-Prime® 3.0 (Psychology Software Tools, Inc., Sharpsburg, Pennsylvania, USA), are detailed as follows:

Belief update task (Fig. 1B). This task was adapted from Yao et al., (2021). Specifically, each trial presented an adverse life event for 2 s, after which participants had 8 s to estimate, and to type down the likelihood of themselves experiencing the event in their future lifetime (first estimation, E1). Following a blank interval (1.2–1.5 s), the feedback probability was shown for 2 s. Following another blank interval (1–1.2 s), participants had 2 s to re-evaluate their prior estimation, and to provide their second estimation (E2) within the next 8 s. Participants were informed that the feedback probability for each adverse life event was obtained from a large-scale study with a demographically similar population. Estimation error (EE) was defined as the differences between feedback probability and participants' first estimation (E1 minus feedback). A trial was classified as desirable (vs. undesirable) when feedback probability was smaller (vs. larger) than E1. Immediate belief updating was calculated as the differences between participants' second and first estimation (i.e., E1-E2 for desirable; E2-E1 for undesirable).

Recall Task. Participants were instructed to recall the previously presented feedback probability, prompted by each adverse life event. Each trial began with an adverse life event presentation (2 s) from the earlier belief update task, followed by a question mark (1s). Participants were given 8s to type down their remembered feedback probability. The Memory error was calculated as the absolute difference between recalled probability and presented feedback probability, i.e., |feedback-recall|, with larger values indicating higher memory errors.

Day 2 Estimation Task. Participants were presented with each of the 96 adverse life events from Day 1 and gave their third estimation (E3) without the presentation of any feedback. Delayed belief updating was calculated as the differences between participants' third and first estimation (i.e., E1-E3 for desirable; E3-E1 for undesirable).

The participant-level optimism updating bias was calculated using immediate/delayed desirable updating minus immediate/delayed undesirable updating, with larger values indicating higher updating for desirable than for undesirable feedback, i.e., optimism biases.

Simplified Mental Rotation Task. This task was adapted from previous research, and was used to minimize individual differences in mental states during tACS (Kasten et al., 2019). During the task, a total of ten uppercase letters, with each letter repeating twice, would be presented in either normal or mirrored orientation. The inter-trial interval (ITI) randomly varied between 10 to110 seconds. Participants had to discern the orientation of the letter within a maximum of 5 seconds by pressing the space bar. Participants were instructed to relax while focusing on the screen to ensure timely responses to the letters.

Assessment of adverse life events. Participants rated each life event on a 6-point Likert scale across four dimensions: personal relevance, familiarity, vividness, and prior experience.

Details on the estimation error (EE) manipulation and event rating are presented in the supplement materials.

Electroencephalography (EEG) Data Acquisition

EEG data were recorded using a Brain Products Brain Vision Recorder (Brain Products GmbH, Munich, Germany) with 64 active Ag/AgCl electrodes mounted in a cap and located in the standard positions according to the International 10–10 system. The ground electrode was positioned at AFz, the online reference was positioned at FCz, and the electrode impedance was kept below 20 KΩ. The sampling rate was 1000 Hz using a BrainAmp AC amplifier (Brain Products GmbH, Munich, Germany).

Transcranial alternating current stimulation (tACS) protocol

Randomization

Participants were randomly assigned to one of the three groups (IAF-tACS, 40 Hz-tACS, or sham), with no more than two consecutive similar assignments. After recruiting approximately 20 participants per group, a gender imbalance emerged, with only five males in the 40 Hz-tACS group and six in the IAF-tACS group. To address this, male participants were randomly assigned to the sham or 40 Hz-tACS groups, while female participants to the IAF-tACS or sham group until an equal gender distribution was achieved across the groups. Subsequently, random allocation resumed. Group allocation remained blinded to the participants.

Determination of IAF and Individual Current Intensity

The two-minute eyes-open resting-state EEG data collected prior to the stimulation was analyzed to determine the IAF for the IAF-tACS group. Artifact-free EEG segments were identified through visual inspection and further cleaned using independent component analysis (ICA) with the *ICLabel* plugin (v1.2.6, Pion-Tonachini et al., 2019) in EEGLAB (Delorme & Makeig, 2004). The IAF calculation was performed on the clean EEG data from frontal and parietal electrodes (F4, F3, Pz, and an averaged across a right frontal electrodes cluster comprising F4, F2, FC4, F6, and AF4). The Fast Fourier Transform (FFT) method was utilized to obtain the IAF. For the gamma-tACS group, we used a fixed 40 Hz as the input frequency. While calculating the IAF, each participant's individual current intensity was determined through a protocol that began at an intensity of 0.5 mA and was increased in 0.1 mA increments until the participant reported discomfort. This process usually finished within one minute, followed by another one-minute stimulation using the intensity so that participants became habituated to the sensations. The mean intensity was 0.57 ± 0.14 mA (M ± SD).

TACS set-up

Stimulation was administered using an HD-tACS system (Soterix Medical, New York, NY) with a 4 × 1 montage (Fig. 1C and 1D). The central electrode was placed over the F4 electrode, with the neighbouring electrodes over Fz, C4, FT8, and FP2 (International 10–10 Modified Combinatorial Nomenclature). The tACS was delivered at an individual current intensity. Participants were informed about potential altered sensations during stimulation before testing individual current intensity. Furthermore, a one-minute stimulation was administrated to all groups before the 15-minute tACS session to familiarize participants with the sensations elicited by the electrical stimulation. For the IAF tACS and 40 Hz tACS groups, the current was ramped up from zero to each participant's individual current density, which was then maintained constant for 15 minutes. The sham group received ramped-up stimulation only in the first 30 seconds.

Behavioral Data Analysis

We used R (Version 4.1.3; R Core Team (2020) for statistical analyses and employed linear mixed-effects models (LMMs) to account for various factors and variances. Fixed factors included tACS group, time, and feedback desirability. Consistent with previous research (Sharot et al., 2011; Kuzmanovic et al., 2018; Yao et al., 2021), covariates were trial-wise first estimation (E1), subjective ratings for adverse life events (vividness, personal relevance, familiarity, prior experience), memory error, and differences in trial numbers between desirable and undesirable conditions. Random effects accounted for estimation error (EE), participant and event ID at the trial-level. We used the Satterthwaite's method ('anova' function in the package *"lmerTest"*; Kuznetsova et al., 2020) to test significance levels for fixed effects. Post-hoc analyses were performed with the 'emmeans' and 'emtrends' function in the package "*emmeans"* (Lenth et al., 2022) to investigate significant interaction effects. Unless otherwise specified, post hoc comparisons were corrected using the false discovery rate (FDR) method.

Trial-level analysis on belief updating

To examine the immediate tACS effect as well as the 24-hour delay effect, we ran the LMM with time (pre, post, delay), desirability (desirable, undesirable), and group (IAF, 40 Hz, sham) as fixed factors to predict belief updating (E2-minus-E1 on Day 1, E3-minus-E1 on Day 2). Consistent with previous research, we added covariates including E1, memory error, trial numbers, and event ratings. Random effects included participant, EE, and event ID (full model definition was presented in SOM).

Participant-level analysis on belief updating

We calculated each participant's update bias (i.e., averaged desirable updating -minus- averaged undesirable updating for each participant), and conducted a mixed 3 (time, pre, post vs. delay) * 3 (group, IAF vs. 40 Hz vs. sham) ANOVA with the update bias as the dependent measure. Potential confounds were included as covariates, including E1, memory score, trial number difference between desirable and undesirable conditions, and event ratings for vividness, familiarity, prior experience and personal relevance.

In all above analysis, covariates were z-scored within each participant.

EEG Data Analysis

Resting-State EEG Data Preprocessing

Artifact-free epochs from the eyes-open resting-state EEG data were visually inspected and selected. A minimum of 90 s of artifact-free data per phase was required. After selection, ICA was applied directly to the cleaned data, and eye-movement-related components were removed using *ICLabel* (Pion-Tonachini et al., 2019) in EEGLAB.

Task EEG Data Preprocessing

An unused channel was removed (LZ), leaving data from the remaining 63 channels for the analysis. All EEG processing was performed using MATLAB-2022b and functions from EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) toolboxes. The EEG raw data were downsampled to 250 Hz, and notch filtered at 50 Hz using the PMnotch with an order of 180, and a high pass filter of 0.5 Hz was applied using the ERPLAB plugin. The filter order was set to 2. Bad channels were detected using a trim outlier plugin, followed by visual inspection and interpolation. The common average was then calculated by adding a zero channel to make the data full rank. Continuous EEGs were then epoched into [-1000 to 2000 ms] segments relative to the onset of feedback, and to the question mark before the second estimation, without baseline correction. Visual inspection was conducted to remove epochs with intensive artifact-contamination in order to improve performance of the independent components analysis (ICA). To facilitate ICA, we first removed the interpolated channels and filtering the clean epoched data with a 1 Hz high-pass to enhance ICA performance. Subsequently, the ICA weights and sphere were re-applied to the original cleaned epoch data (with interpolated channels removed). We used the *ICLabel* plugin to remove eye- and muscle-related activity components. The clean ICA-processed data were interpolated for previously removed channels. We then performed an automatic peak-to-peak artifact removal step to handle any remaining epochs with artifacts not captured by ICA. The remaining clean data were used for spectral analysis.

EEG Spectral Analysis

To examine how tACS influenced brain activity during resting and task states, we performed EEG spectral power analysis during eyes-open resting states for a minimum of 90 seconds, and in task states within the first second following the presentation of the feedback probability. We focused on the alpha and gamma frequency bands in the right frontal channels (F2, F4, FC4, F6, AFz). Using Fast Fourier Transforms (FFTs) with Welch's method and a Hanning window, we analyzed alpha power within the Individual Alpha Frequency (IAF ± 2Hz) and the gamma power (30–50Hz) over these five channels on laplacian current source density (CSD) transformed EEG data.

The Frontal Alpha Asymmetry (FAA) was calculated by obtaining raw power from the left F3 and the right F4 (Smith et al., 2017), which was then log-transformed (ln) to assess the difference in alpha power between these electrodes (ln alpha F4 - ln alpha F3). To evaluate the tACS effect on the right frontal EEG power changes, alpha and gamma power were averaged across the five aforementioned channels (F2, F4, FC4, F6, AFz). For resting states, raw power was utilized over the entire 90-second epoch, while for task states, power was normalized against a baseline period (– 1000 to 0 ms) and expressed in decibel units (10log10) in statistical analysis.

To quantify the specific effects of tACS on EEG activity, we employed Analyses of Covariance (ANCOVAs) focusing on frontal alpha asymmetry (FAA), right frontal alpha, and right frontal gamma power, both during resting and the belief update task (involving feedback encoding and re-evaluation processing phases, Fig. 1B). In these ANCOVAs, we used the pre-tACS values of the corresponding outcome measure as covariates to account for baseline differences, and then compared the post-tACS EEG outcome measures across three groups, respectively. For task EEG analyses, it involved 3 (between-subject, tACS groups) by 2 (feedback desirability) by 2 (processing phase) ANCOVAs for each of the three outcome measures.

To investigate the association between EEG activity changes and belief updating changes from pre- to post-tACS, we ran a series of correlation with changes of FAA/right frontal alpha/gamma power and update changes for desirable and undesirable condition separately. All correlations were FDR-corrected for multiple comparisons for the total number of 12 correlations across three groups separately for FAA/right frontal alpha and gamma power.

Results

Behavioral Results

Descriptive of outcomes variables and questionnaire data from the three groups are provided in Supplementary Table S1–3. In the main text, we report results related to our central research questions:

how different tACS administration (40 Hz gamma vs. individualized alpha frequency IAF vs. sham) influenced 1) trial-level belief update toward desirable and undesirable feedback within each participant, and 2) participant-level optimism biases, quantified as the differences between belief update following desirable and undesirable.

Trial-level belief updating toward desirable and undesirable feedback

Our primary analysis focused on the effects of tACS group (40 Hz vs. IAF vs. sham), feedback desirability (desirable vs. undesirable feedback), and time (pre- vs. post-tACS vs. 24-hour delay) on belief updating. Consistent with the valence-dependent belief updating effect, we found a significant main effect of desirability: Participants were more likely to adjust their beliefs following desirable compared to undesirable feedback, i.e., an optimism bias, $F(1, 40) = 7.80$, $p = 0.008$. We also observed a main effect of tACS group, $F(2, 97) = 4.25$, $p = 0.017$, wherein the 40 Hz-tACS group showed significantly higher belief updating than the IAF- and the sham control groups (all *p*s = 0.23), but no difference was found between IAF and sham group ($p = 0.850$).

Most importantly, the three-way interaction (tACS * desirability * time) was significant, $F(4, 16399) = 18.84$, $p < 0.001$. Following up this three-way interaction, we examined belief updating toward desirable and undesirable feedback in different tACS groups across time. We found that in the pre- and post-tACS, the three tACS groups did not differ in belief updating toward neither desirable or undesirable feedback, all *p*s > 0.378. In contrast, in the 24-hour delay session, the 40 Hz tACS group exhibited smaller belief updating toward undesirable feedback relative to both the sham ($\beta = -1.35$, $SE = 0.57$, $p = 0.025$) and IAF-tACS group ($\beta = -2.25$, $SE = 0.56$, $p < 0.001$), together with an increased belief updating toward desirable feedback than both the sham ($\beta = 2.93$, $SE = 0.73$, $p < 0.001$) and the IAF ($\beta = 4.42$, $SE = 0.73$, $p < 0.001$) groups. For participants in the IAF-tACS group, while belief updating to undesirable feedback was not significantly different from the sham group ($\beta = -0.90$, $SE = 0.56$, $p = 0.110$), they showed reduced belief updating to desirable feedback ($\beta = 1.49$, $SE = 0.73$, $p = 0.042$, Fig. 2).

Participant-level optimistic updating biases

When examining participant-level optimistic updating biases (desirable updating minus undesirable updating) in a 3 (group, between-subject, 40 Hz vs. IAF vs. sham) by 3 (*time*, within-subject, pre- vs. post- vs. delay) mixed ANOVA, we observed a significant *g*roup * *time* interaction, $F(4, 371) = 3.72$, $p = 0.006$, *partial* $\eta^2 = 0.05$ (Fig. 3). Post hoc comparisons revealed that in the delay session, the 40 Hz-tACS group exhibited a significantly larger updating bias than the sham group ($p = 0.006$) and the IAF group ($p < 0.001$), while the IAF group had a numerically smaller updating bias than the sham group that did not reach significance, $p = 0.076$. No significant differences were found in either pre- or post-*tACS*, all *p*s > 0.908. When comparing updating biases across *time*, we found that both sham and 40 Hz tACS group showed increased optimistic updating biases in the delay as compared to pre- and post-tACS (all ps <

0.05), replicating our previous results on the long-term optimistic bias (Yao et al., 2021). On the other hand, the IAF group did now show this effect (all ps = 0.838).

Collectively, both trial- and participant-level analyses showed that the optimism biases became larger over time. Most importantly, in the delay session, the 40 Hz-tACS group demonstrated significantly larger optimism biases than the sham group, while the IAF group did not significantly differ from the sham group.

EEG Spectrum analysis

Fifteen participants with less than 90 seconds of clean resting EEG data were excluded from this analysis. During post-tACS resting states, the one-way ANCOVA revealed no significant differences between the three groups in either FAA, $F(2, 71) = 1.53$, $p = 0.223$, or right frontal alpha power, $F(2, 71) = 0.13$, $p = 0.875$, or right frontal gamma power, $F(2, 71) = 1.02$, $p = 0.365$, indicating an absence of tACS effect on the resting states EEG power.

In the task EEG analysis on gamma power, the mixed ANCOVA—with group, desirability, and processing phase as factors, and controlling for pre-tACS gamma power as a covariate, showed a significant main effect of group, $F(2, 359) = 4.76$, $p = 0.009$, partial $\eta^2 = 0.01$. However, the follow-up analyses showed no significant contrasts were found (all ps > 0.102). Importantly, a significant interaction between group and desirability was observed, $F(2, 359) = 3.14$, $p = 0.045$, partial $\eta^2 = 0.02$. As can be seen in Fig. 4, 40 Hz tACS group showed greater right frontal gamma power than sham and IAF groups only in desirable condition (40 Hz vs. sham: $p = 0.008$; 40 Hz vs. IAF: $p = 0.025$). No other significant contrasts were found (all ps > 0.373).

No significant effect of group or interactions between group and other factors were detected for alpha power or FAA (all ps > 0.259). Together, these results underscore the frequency-specific impact of tACS on modulating optimistic belief updating.

Regarding the relationship between EEG activity changes and behavioral belief updating changes, we found no significant correlations between FAA, right frontal alpha or gamma power and updates from either desirable or undesirable feedback, respectively (all ps > 0.311).

Discussion

In this study, we explored the influence of right frontal HD-tACS on optimistic belief updating. We administered a single session of IAF-, 40 Hz-, and sham-tACS stimulation to three groups of participants. We found that across all three groups, participants preferentially used desirable over undesirable feedback to update their prior beliefs, replicating the optimistic belief updating effect (Sharot et al., 2011; Sharot & Garrett, 2016; Kuzmanovic & Rigoux, 2017; Kuzmanovic et al., 2018; Garrett et al., 2018). This optimistic bias became larger over time (see Yao et al., 2021). Notably, the 40 Hz-tACS significantly increased the 30–50 Hz gamma power immediately after stimulation exclusively in desirable feedback condition, and also increased optimistic belief updating after 24 hours compared to the sham/IAF-tACS groups.

Our findings indicated that the 40 Hz-tACS significantly augmented the 30–50 Hz EEG power during the processing of desirable feedback, particularly enhancing optimism biases following a 24-hour delay. The effectiveness of 40 Hz-tACS in our study was in line with prior studies. For example, research suggests that the gamma tACS over the frontal region amplifies prefrontal cortical activity (Mencarelli et al., 2022), which is instrumental in contextual information representation (D'Ardenne et al., 2012) and belief updates under uncertainty (Schulreich & Schwabe, 2021). Furthermore, gamma tACS has been shown to enhance various cognitive functions (Nissim et al., 2023). For example, gamma tACS selectively bolstered working memory capabilities (Hoy et al., 2015), promoted logic reasoning (Santarnecchi et al., 2013), and generated long-lasting enhancements in memory (Grover et al., 2022). Based on these results, enhancing gamma activity could encourage individuals to engage more proactively with positive stimuli, such as the desirable feedback in the belief update task. This observation was supported by findings that 40-Hz tACS enhanced gamma power toward desirable feedback, as compared to the sham group, but not when processing undesirable feedback. Furthermore, this dissociation also suggested that external brain stimulation may selectively modulate internal motivational states and information processing in a valence-dependent manner.

Together, the observed delayed effects of 40 Hz-tACS underlined the critical role of the offline period in mediating tACS's long-lasting behavioral impacts. This observation underscored the possibility that the influence of tACS may extend beyond immediate neural excitation, necessitating a period of offline processing for the full realization of its behavioral impact (Elyamany et al., 2021; Grover et al., 2022; Kasten et al., 2016; Shtoots et al., 2024). For example, single-session frontal midline theta tACS has been shown to result in a significant enhancement of free recall performance that persists up to a week following the tACS (Shtoots et al., 2024). In addition, multiple-session dorsolateral prefrontal cortex (DLPFC) gamma tACS selectively and sustainably improves long-term memory in older adults, with benefits persisting for at least 1 month (Grover et al., 2022). These findings suggest that the neuroplastic changes induced by tACS may be consolidated during the post-stimulation offline period. Additionally, the potential of 40 Hz tACS to alter a pessimism mindset, opens avenues for therapeutic applications, particularly for individuals with depression or those who show deficits in optimistic processing (Hobbs et al., 2022; Korn et al., 2014). Therefore, to validate these findings and understand their clinical relevance, future studies are encouraged to assess the efficacy of 40 Hz-tACS in depressed populations, thereby bridging the gap between experimental results and therapeutic potential.

Regarding the effect of IAF-tACS, we initially hypothesized that using tACS targeting the right frontal cortex could enhance alpha power, which subsequently change frontal alpha asymmetry and motivational states (Alexander et al., 2019; S. Liu et al., 2023; Riddle et al., 2022). However, tACS at individual participant's peak alpha frequency did not modulate alpha power, at least with one single session. Nevertheless, it is important to consider the complexity of tACS effects and the specific conditions under which it may modulate frontal alpha activity. A recent meta-analysis revealed that IAF-tACS did not significantly modulate alpha band power (Millard et al., 2023), possibly due to several reasons such as differences in tACS parameters, the positioning of electrodes, and the timing of IAF measurement. For instance, Alexander et al. (2019) and Riddle et al. (2022) used bi-frontal stimulation, with two central stimulation sites placed at electrodes F3 and F4, and a returning site placed at Cz. However, such bi-frontal stimulation only changed left, but not right, frontal alpha power, suggesting a potential hemispheric difference in the sensitivity to tACS. Future studies shall utilize within-subject designs to further explore the relationship between frontal alpha activity and belief updating by applying tACS separately over the left and right frontal cortex, acknowledging the variability in brain function lateralization among individuals. In addition, while we aligned the stimulation frequency with individual endogenous alpha peak frequencies, these alpha peak frequencies may vary between task and resting states (Stecher et al., 2017; Vossen et al., 2015). Future research shall consider examining individual alpha peak frequencies during the task-of-interest, and adjust the stimulation frequency throughout the experiment to increase optimal efficacy.

Limitations and future directions shall be discussed. First, we identified the IAF during a brief 2-minute resting state for tACS application in a mental rotation task. However, this approach may not fully capture the dynamic neural activities essential for tasks involving belief updating, highlighting the complexity in the interaction between brain activity and external stimulation (Bradley et al., 2022; Kasten & Herrmann, 2022). For a more comprehensive understanding, it is crucial that future studies shall systematically align the IAF with either task-specific or alternative frequencies, to increase stimulation precision. Second, the study's reliance on a single tACS session could limit the detection of enduring or robust stimulation effects. Drawing from previous research (Manippa et al., 2023), multiple sessions of tACS may produce cumulative effects. Therefore, future studies should consider multiple stimulation sessions to capture the potential influence of HD-tACS on optimistic belief updating. Additionally, to ensure the generalizability of the findings, it is imperative to replicate the study using more diverse samples, such as among different age groups, clinical populations, and individuals exhibiting a range of baseline optimism biases (Schutter et al., 2023).

Conclusion

To conclude, our study examined the effects of right frontal cortex HD-tACS on optimistic belief updating. We found that 40 Hz-tACS amplified the long-term optimistic belief updating bias, while IAF-tACS tended to diminish this bias. These findings highlight the frequency-specific effects of tACS on belief updating, and the tACS effect may require offline processing to emerge. If gamma stimulation amplifies optimistic biases, our study bears potentials in developing novel tACS-based interventions to reduce pessimistic thinking, and eventually restore optimistic outlooks.

Declarations

Availability of data and materials

All data and the code that support the findings of this study are available in the Open Science Framework (https://osf.io/2ez9y/?view_only=f8b89b1b5da54f23a93b7eafbe091225).

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Author contributions

Conceptualization: Z. Y. and X. H. **Methodology:** Z. Y., J. W., G. H., L.L., Z. L., Z. Z., and X. H. **Data Curation:** Z. Y., and J. W. **Formal Analysis:** Z. Y., J. W., Z. Z. and X. H. **Investigation:** Z. Y., and J. W. **Software:** Z. Y. **Visualization:** Z. Y., and J. W. **Writing – Original Draft Preparation:** Z.Y., X. H., and Z. Z. **Writing – Review & Editing:** Z.Y., J.W., G. H., L. L., Z. L., L. Z., H. W., T. Y., Z. Z., X. H. **Supervision:** X. H. and Z. Z. **Project Administration**: Z. Y. **Funding Acquisition:** X. H., and Z. Z..

Ethical Approval

The Human Research Ethics Committee of Shenzhen University approved the study (application number PN-202300056) and all participants gave their written consent.

Consent to publication

Not applicable.

Competing interests

The authors declare no competing interests.

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Figures

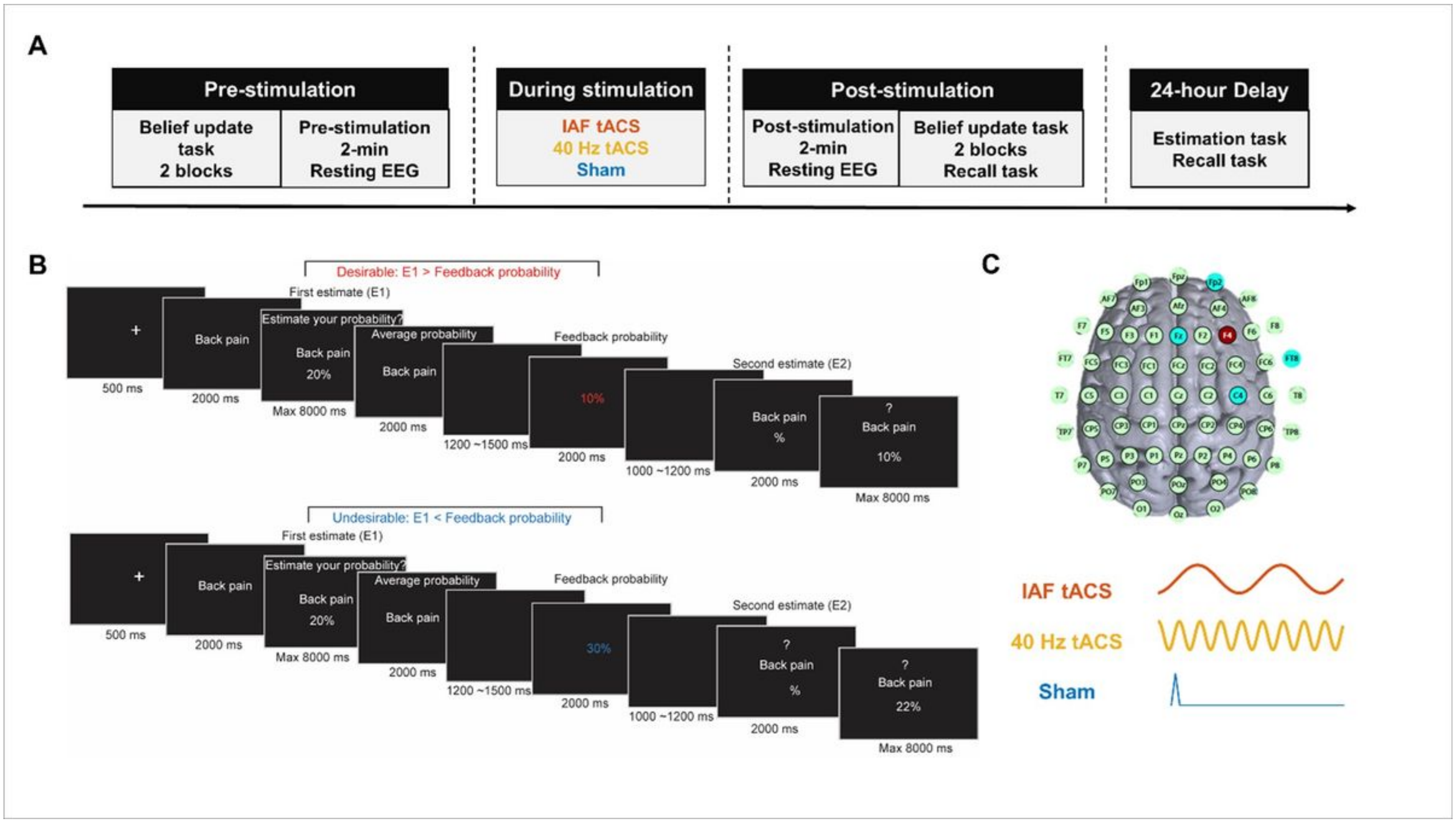

Figure 1

An overview of the experimental procedure, belief update task, and the tACS montage (A) Timeline of experimental tasks during the immediate session. The belief update task contained four blocks, with two blocks implemented pre-tACS and two blocks implemented post-tACS. (B) A schematic trial illustration of the belief update task. On each trial, participants were presented with an adverse life event and were asked to estimate how likely the event would occur to them in the future. After receiving the feedback probability, participants were given 2 seconds to re-evaluate their estimation and then provided a second estimate (E2) within the same trial (upper panel: desirable condition; lower panel: undesirable condition). (C) tACS/EEG Montage for right frontal stimulation. HD-tACS electrodes were positioned at F4 (red electrode = center) and Fz, C4, FT8, and FP2 (blue electrodes = return). Abbreviations: IAF = individualized alpha frequency.

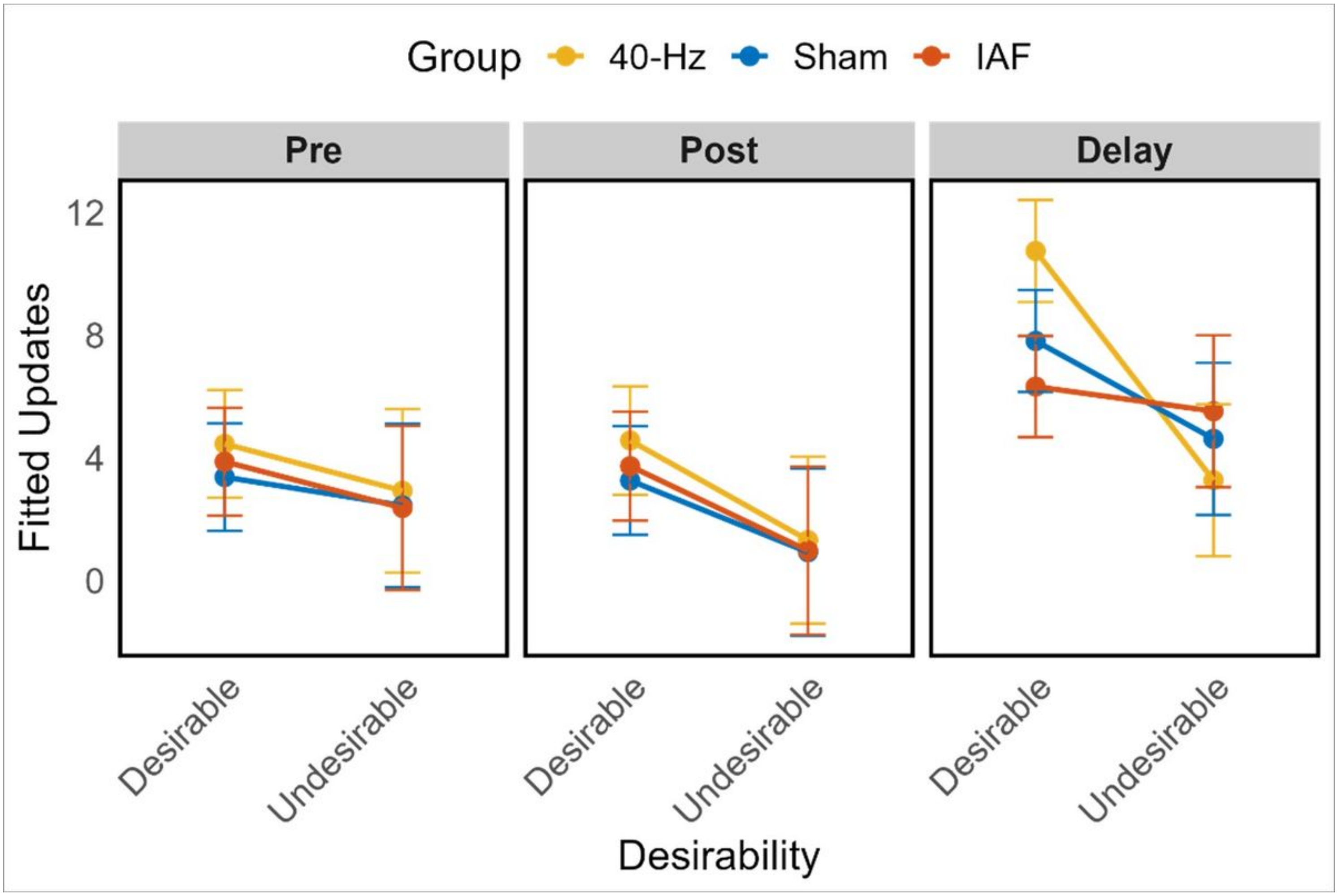

Figure 2

Interaction effects of group, desirability, and time on belief updating toward desirable and undesirable feedback. Error bars indicate 95% confidence intervals (CI).

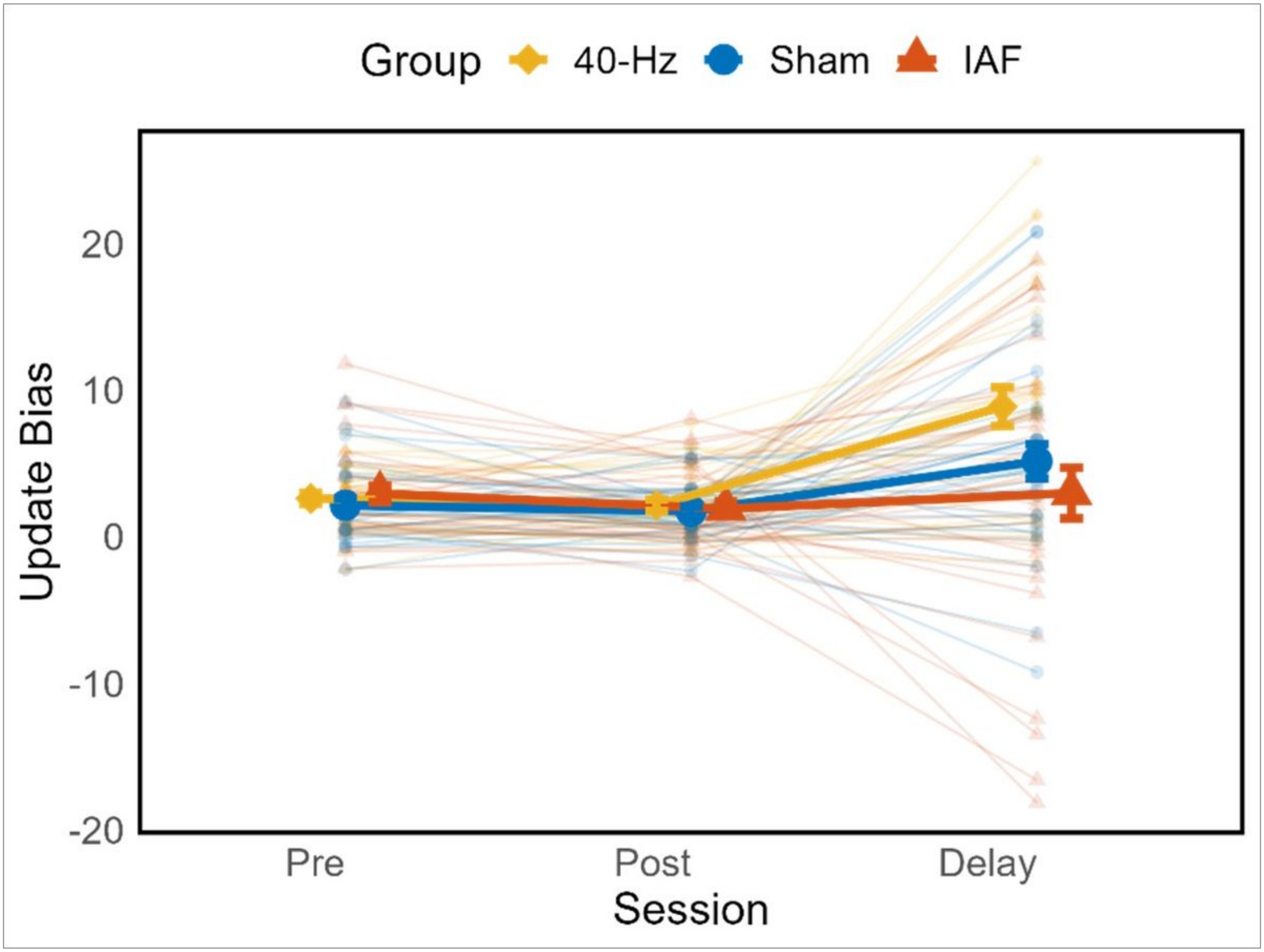

Figure 3

Interaction effects between group and time on optimistic belief updating biases. Transparent lines represent individual data at each test session. Error bar represents the standard error of the mean (SEM).

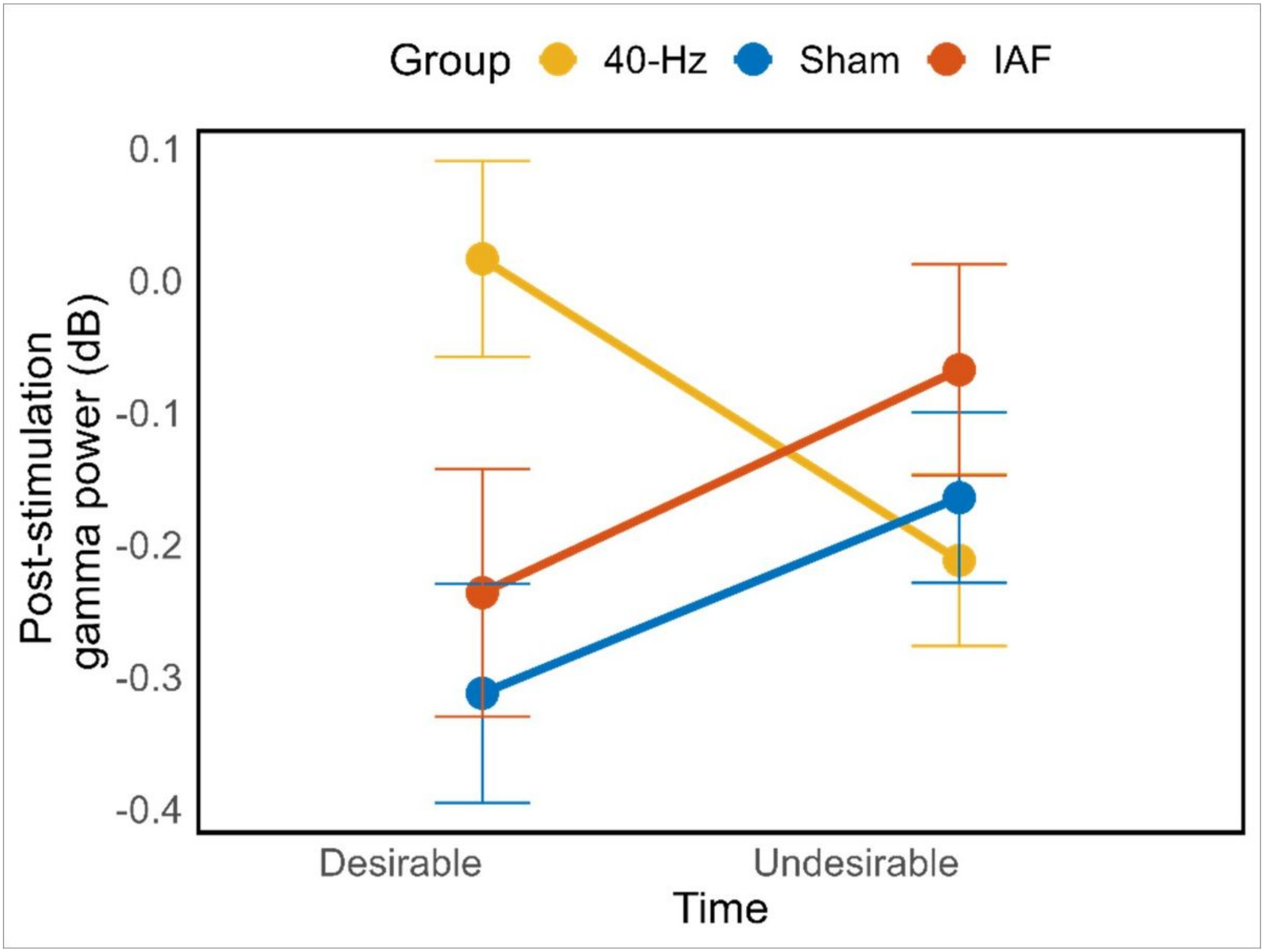

Figure 4

Interaction effects of group and desirability on post-tACS gamma power. Error bars indicate standard error of the mean (SEM).

Supplementary Files

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