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LETTER TO THE EDITOR

Right Frontal Gamma Transcranial Alternating Current Stimulation Modulates Optimism Biases

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Dear Editor,

People are often optimistic when forecasting the future, such that they believe they are less likely to encounter adverse life events. This phenomenon, known as optimism bias, emerges due to preferential encoding and consolidation of desirable over undesirable information [1, 2], engaging frontal brain regions such as the anterior cingulate cortex and inferior frontal gyrus [1]. An optimism bias is instrumental in supporting mental health: reduction or absence of optimism biases is associated with mood disorders such as depression, characterized by pessimistic thinking about the future [3]. This relationship highlights the potential value of interventions that could enhance optimism bias [4].

Recent developments in non-invasive brain stimulation techniques, especially transcranial alternating current stimulation (tACS), have drawn significant interest for their potential to modulate neural activity and cognitive-affective processing in humans [5]. Related to optimism bias, patients with major depressive disorder exhibit frontal alpha asymmetry–a notable difference in alpha power between the right and left hemispheres [6]. This asymmetry correlates with negative emotional processing involving the amygdala and the dorsolateral prefrontal cortex [7]. In addition, the 30-80 Hz gamma-band activity over the frontal cortex is crucial for high-level cognitive processing such as attention, memory, and executive control [5]. These processes are essential for the formation or updating of belief systems, including optimism bias. Previous studies have also suggested a link between reduced gamma-band EEG power and depressive symptoms [8], especially in the prefrontal cortex [9]. Based on these findings on alpha and gamma, and their links with depressive symptoms and optimistic biases, here we proposed to investigate whether alpha- and gamma-band tACS can affect optimism biases.

Here, in a frequency-/sham-controlled, single-blind, between-subject design, we administered a single session of high-definition tACS (HD-tACS) to three groups of

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participants: gamma-tACS, alpha-tACS, and a sham control group (Fig. 1). Participants were randomly assigned to one of the three groups (IAF-tACS, 40 Hz-tACS, or sham), with no more than two consecutive participants assigned to the same group. The final sample included 31 participants in the alpha-tACS group (18 males, aged 20.52 ± 1.48 years), 31 participants in the 40 Hz-tACS group (12 males, aged 20.45 ± 1.48 years), and 31 participants in the sham control group (16 males, aged 20.66 ± 1.94 years). For a comprehensive description of the participant inclusion criteria, please refer to the Supplementary Materials. For alpha-tACS, we applied an individualized alpha frequency (IAF) to increase the precision of alpha modulation. For gamma tACS, we used a frequency fixed 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. To assess optimism biases, we applied a belief update task in which participants would update the likelihood of experiencing adverse life events happening to them in the future (e.g., developing back pain when 60 years old), following desirable and undesirable feedback provided for their first estimate [1, 2]. Optimism biases were evident if participants preferentially used desirable than undesirable feedback to update their earlier likelihood estimate. The Supplementary Materials included the following details: inclusion/exclusion criteria of participants, experimental design and task procedures, tACS setup, behavioral and EEG data analysis, and statistical analysis methods.

To assess the immediate tACS effect as well as the 24-h delayed effect, we ran a linear mixed model (LMM) with the tACS group (IAF *vs* 40 Hz *vs* sham), time (pre *vs* post *vs* delayed), and desirability (desirable *vs* undesirable) as fixed factors, and participant as a random factor to predict belief updating (E2 -minus- E1 on Day 1, E3-minus-E1 on Day 2). This LMM revealed a significant desirability effect: Participants were more likely to update their beliefs following desirable than undesirable feedback, i.e., an optimism bias, F (1, 40) = 7.80, P = 0.008. Most importantly, the three-way interaction (tACS by time by desirability) was significant, F (4, 16399) = 18.84, P <0.001. We found that the three tACS groups only differed in the delayed test: the 40 Hz tACS group exhibited smaller

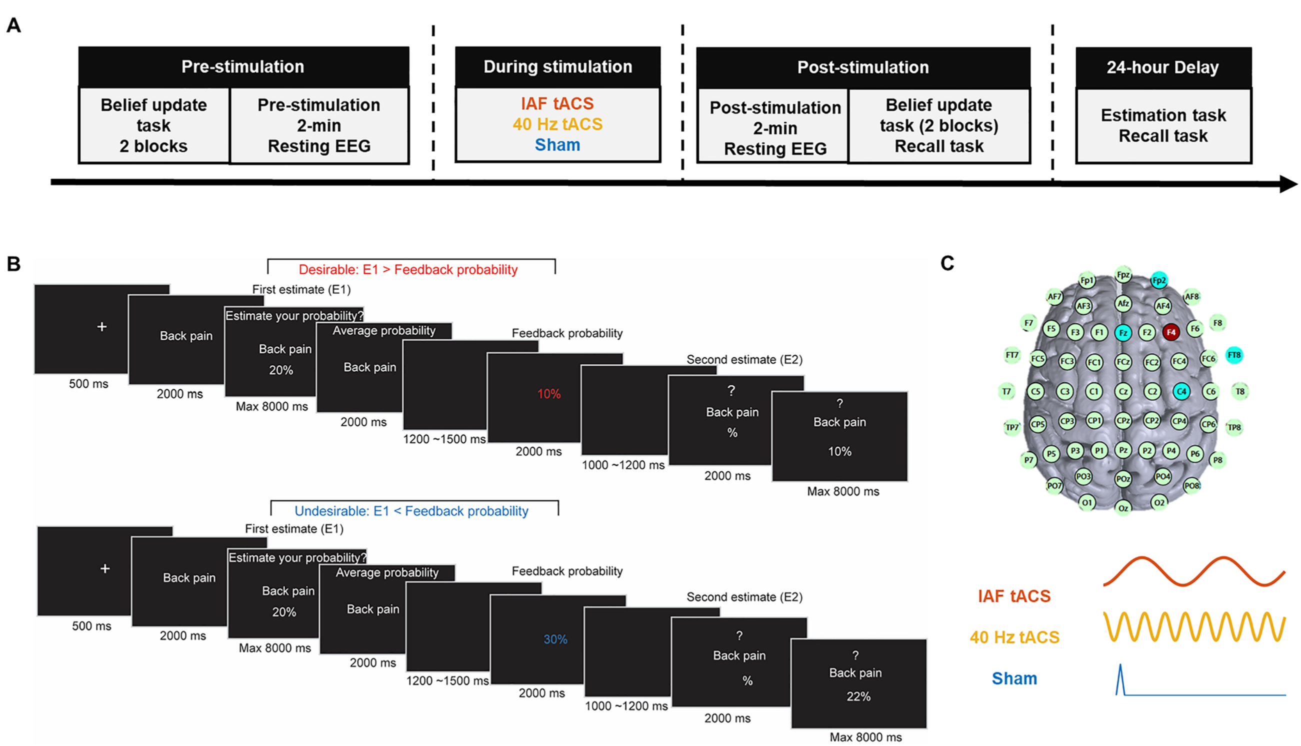

Fig. 1 An overview of the experimental procedure, belief update task and the tACS montage. **A** Timeline of experimental tasks during the immediate session. The belief update task contains four blocks, with two blocks implemented pre-tACS and two blocks implemented post-tACS. **B** A schematic trial of the belief update task. On each trial, a participant is presented with an adverse life event and is asked to estimate how likely the event would occur to them in the future. After receiving the feedback probability, the participant is given 2 s to re-evaluate their estimation and then provided a second estimate (E2) within the same trial (upper panel: desirable condition; lower panel: undesirable condition). About 24 h after the Day 1 session, the participant returns to the lab to finish a surprise belief update task to assess delayed optimism bias. **C** tACS/EEG montage for right frontal stimulation. HD-tACS electrodes are positioned at F4 (red electrode = center) and Fz, C4, FT8, and FP2 (blue electrodes = return). IAF, individualized alpha frequency.

belief updating toward undesirable feedback relative to 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 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. 2A). In the pre- and post-tACS groups, the three tACS groups did not differ ($P > 0.378$).

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* delayed) mixed ANOVA, we found a significant group × time interaction, F (4, 371) = 3.72, $P = 0.006$, *partial* $\eta^2 = 0.05$ (Figure 2B). *Post hoc* comparisons revealed that in the delayed 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 showed numerically smaller updating biases than the sham group that did not reach significance ($P = 0.076$). No significant between-group differences were found in either pre- or post-tACS, all

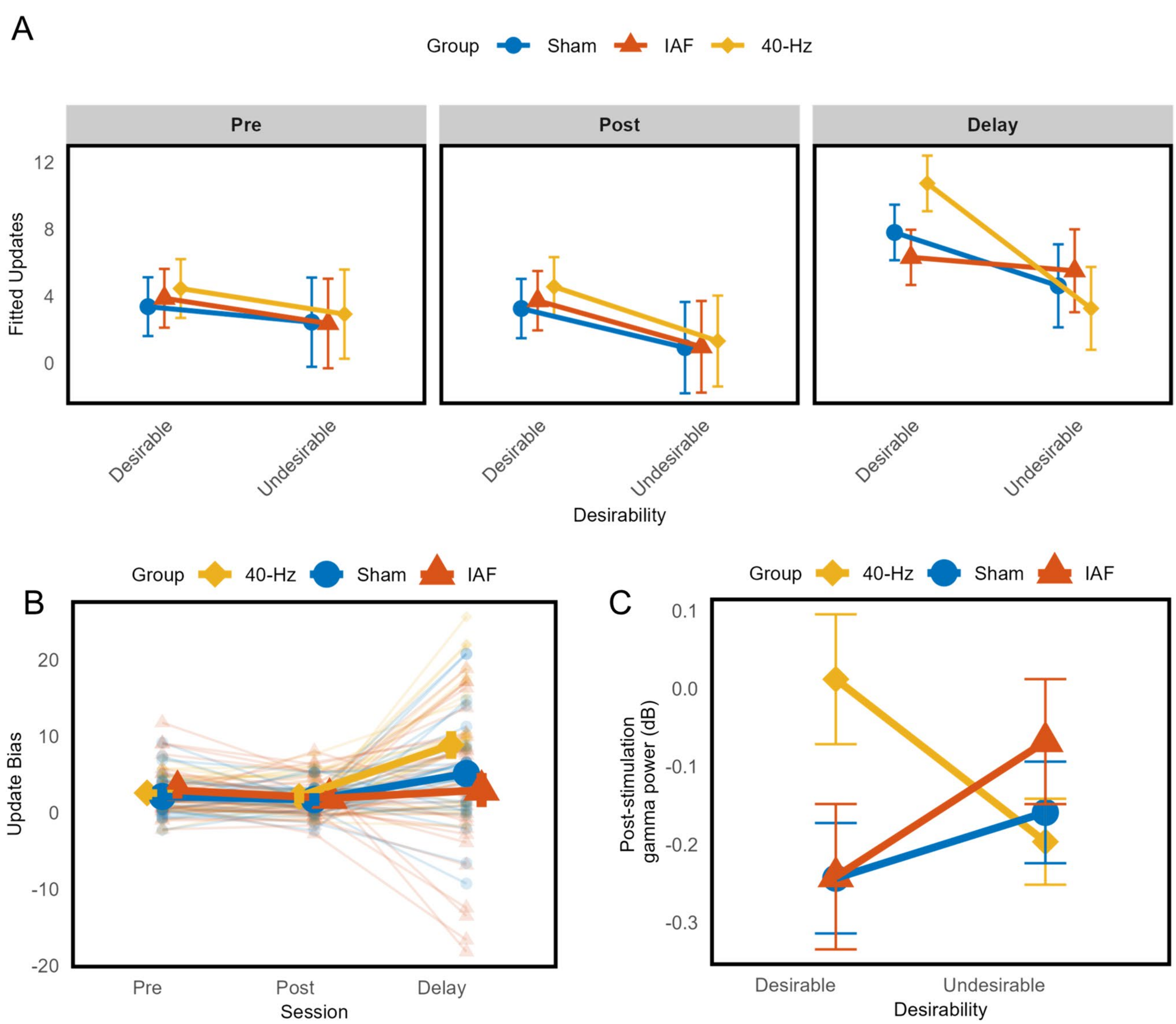

Fig. 2 **A** Interaction effects of group, desirability, and time on belief updating toward desirable and undesirable feedback. Error bars indicate 95% confidence intervals. **B** Interaction effects between group and time on optimistic belief updating biases. Transparent dots represent individual data at each test session. **C** Interaction effects of group and desirability on post-tACS gamma power. Error bars indicate the standard error of the mean.

$P > 0.907$. When comparing updating biases across time, we found that both the sham and 40 Hz tACS groups, but not the IAF group, showed increased optimistic updating biases in the delay as compared to pre- and post-tACS ($P < 0.05$ for sham and 40-Hz group, see Yao *et al.* [2], $P = 0.838$ in the IAF group).

Collectively, both trial- and participant-level analyses showed that in the delayed 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.

Given that the 40-Hz tACS group showed enhanced optimism biases, we next examined the changes in EEG gamma power that may underlie the behavioral changes. We applied a mixed ANCOVA, with group, desirability, and processing phase (feedback processing *vs* second estimation [E2], Fig. 1B) as factors, and controlling for pre-tACS gamma power as a covariate. We found a significant group by desirability interaction, F (2, 359) = 3.62, $P = 0.028$, partial $\eta^2 = 0.02$. The 40-Hz tACS group showed greater right frontal gamma power than the sham and IAF groups only in desirable conditions (40 Hz *vs* sham: $P = 0.026$; 40 Hz *vs* IAF: $P = 0.011$, Fig. 2C). No other significant contrasts were found (all $P > 0.447$). No significant effect of group or interactions between group and other factors were detected for alpha power or frontal alpha asymmetry (all $P > 0.111$). Together, these results underscore the frequency-specific impact of tACS on modulating delayed optimistic belief updating.

Our findings showed that the 40-Hz tACS significantly augmented the 30–50 Hz EEG power during the processing of desirable feedback, and enhanced optimism biases following a 24-h delay. The benefits of 40-Hz tACS were in line with prior studies. For example, gamma tACS enhances various cognitive functions, including logical reasoning [10] and memory performance [11]. Therefore, enhancing gamma activity could facilitate the encoding and use of desirable feedback in the belief update task. Indeed, the 40-Hz tACS (*vs* sham) enhanced gamma power in processing desirable (*vs* undesirable) feedback. This finding suggested that non-invasive brain stimulation tunes the brain into preferential processing of motivationally salient information (i.e., desirable feedback). Intriguingly, the benefits of gamma in promoting optimistic biases were evident only after 24 h, highlighting the importance of the offline period in fortifying the effects of gamma tACS.

Regarding the effect of IAF tACS, we initially hypothesized that by targeting the right frontal cortex, IAF tACS could enhance alpha power over this region. This enhancement would subsequently change frontal alpha asymmetry, thereby inducing an approach motivational tendency to process desirable feedback [12]. However, tACS at the IAF did not modulate alpha power, at least with a single session of tACS. 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 does not significantly modulate alpha band power [13], possibly due to differences in tACS parameters, the positioning of electrodes, and the timing of IAF measurement, among others. Future studies using within-subject designs are needed 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 functional lateralization among individuals.

It is noteworthy that we did not include individuals with severe depressive symptoms. By examining a healthy population, we aimed to understand how tACS can modulate brain activity related to optimism bias, which is crucial for subsequent research using similar techniques among clinical populations. Our findings provide data that can be directly applied to depression that is characterized by impaired optimism biases. By elucidating the neural mechanisms among healthy individuals, we can design more effective tACS interventions for depressive patients. Furthermore, while our study applied single-session tACS to examine its immediate effects, future research could investigate the efficacy of multisession 40-Hz tACS, which holds the potential for greater effect sizes and longer-lasting benefits [14]. This can particularly benefit depressive individuals who harbor deep-rooted pessimistic beliefs about their future or themselves. In addition, research has suggested that combining brain stimulation with cognitive tasks can further enhance intervention efficacy [15]. Therefore, integrating multisession tACS with belief updating tasks could be crucial to achieving sustained benefits in enhancing optimism.

In summary, we examined the effects of right frontal cortex HD-tACS on optimistic belief updating. We found that 40-Hz tACS enhanced long-term optimistic belief updating biases, while IAF tACS tended to diminish this bias. These findings highlight the frequency-specific effects of tACS on belief updating, and the tACS-induced behavioral benefits may require offline processing to emerge. The potential of 40-Hz tACS in enhancing optimistic processing opens avenues for therapeutic applications, particularly among depressive individuals who are characterized by pessimistic thinking styles [3]. Future studies are encouraged to directly test this possibility in clinical settings, bridging experimental findings and therapeutic potential.

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Competing interests The authors declare no competing interests.

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