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RESEARCH REPORT

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Midfrontal theta transcranial alternating current stimulation modulates behavioural adjustment after error execution

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Abstract

Cognitive control during conflict monitoring, error processing, and post-error adjustment appear to be associated with the occurrence of midfrontal theta (MFΘ). While this association is supported by correlational EEG studies, much less is known about the possible causal link between MFΘ and error and conflict processing. In the present study, we aimed to explore the role of band-specific effects in modulating the error system during a conflict resolution. In turn, we delivered transcranial alternating current stimulation (tACS) at different frequency bands (delta δ, theta θ, alpha α, beta β, gamma γ) and sham stimulation over the medial frontal cortex (MFC) in 36 healthy participants performing a modified version of the Flanker task. Task performance and reports about the sensations (e.g. visual flickering, cutaneous burning) induced by the different frequency bands, were also recorded. We found that online θ-tACS increased the response speed to congruent stimuli after error execution with respect to sham stimulation. Importantly, the accuracy following the errors did not decrease because of speed-accuracy trade off. Moreover, tACS evoked visual and somatosensory sensations were significantly stronger at α-tACS and β-tACS compared to other frequencies. Our findings suggest that theta activity plays a causative role in modulating behavioural adjustments during perceptual choices in a stimulus-response conflict task.

KEYWORDS
cognitive control, midfrontal theta, performance monitoring, post-error slowing, transcranial alternating current stimulation

Abbreviations: AC, alternating current; Acc, accuracy; CC, congruent condition; EEG, electroencephalography; ERN, error-related negativity; ERP, event-related potentials; IC, incongruent condition; MFC, medial frontal cortex; MFΘ, midfrontal theta; MSE, mean squared error; PES, post-error slowing; RTs, reaction times; SAT, speed-accuracy tradeoff; tACS, transcranial alternating current stimulation; θ, theta.

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1 | INTRODUCTION

The complexity that characterizes our decisions and actions may cause conflicts and lead to an erroneous performance in a variety of circumstances. Conflict and error monitoring are two distinct but intimately connected aspects of cognitive control which are called into play when two mutual responses are activated and a mismatch between intended and actual responses is detected (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Holroyd & Coles, 2002). These two cognitive components represent an essential requisite for efficiently driving human behaviour.

Control mechanisms that prevent the repetition of errors and allow for adaptive changes of performance seem to be underpinned by specific cortical networks centered upon the frontal regions (Reinhart & Woodman, 2014; Yeung, Botvinick, & Cohen, 2004). Post-Error Slowing (PES), that is the reduced response speed following execution of an error is a classical example of behavioural adaptation that drives one to implement a prudent, conservative response strategy (Rabbitt & Rogers, 1977). Such self-regulative processes minimize the likelihood that an error is repeated later in a sequence (Danielmeier & Ullsperger, 2011).

Recent electroencephalographic (EEG) and neuroimaging studies in human and non-human primates indicate that the medial frontal cortex (MFC) may represent a computational hub for cognitive control connected to different neural systems involved in sensory, emotional, motivational, and social processing (Cohen, 2011; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). This hub may play a pivotal role in the top-down modulation of behaviour (Cohen & Donner, 2013; Hayward, Goodwin, & Harmer, 2004; Rushworth, Kennerley, & Walton, 2005). Theta-band (θ, 4–7 Hz) is a rhythmic endogenous oscillation recorded across several areas of the brain and associated with high-order cognitive functions (Cavanagh & Frank, 2014; Nigbur, Ivanova, & Stürmer, 2011; Raghavachari et al., 2006; Solomon et al., 2017). Enhancement of theta activity can be recorded along the frontal midline cortex during conflict, error, and top-down adjustment of behaviour (Cavanagh & Shackman, 2015; Cohen, Ridderinkhof, Haupt, Elger, & Fell, 2008; Luu, Tucker, & Makeig, 2004; van Noordt, Campopiano, & Segalowitz, 2016). These electro cortical oscillations, named midfrontal theta (MFΘ), may act as an endogenous synchronizer when control is requested (Cavanagh & Frank, 2014). In addition, evidence from EEG shows that MFΘ increases over the MFC (especially under the FCz electrode position) when the resolution of a conflict-related task is required, that is in the Flanker and Stroop tasks (Cohen & Donner, 2013; Cohen et al., 2008; Taylor, Stern, & Gehring, 2007). This result led scholars to theorize that MFΘ is a sort of *lingua franca* (Cavanagh, Zambrano-Vazquez, & Allen, 2012) through which adaptive adjustment is implemented in situations where stimulus-response conflicts experimentally arise (van Noordt et al., 2016). Therefore, the role of frontal neural computations based on theta oscillations would seem to be associated with cognitive control. However, due to the correlational nature of the aforementioned findings, it is not completely clear if MFΘ would reflect an active mechanism for communicating detailed information to distal areas involved in top-down control, a generic alarm signal, or solely an epiphenomenon generated by different processes that occur within the brain (Cavanagh & Frank, 2014). In this sense, modulating the medial frontal cortex in theta frequency may be an innovative approach to shed new light on this issue.

Transcranial Alternating Current Stimulation (tACS) is a non-invasive modulatory technique that allows us to test the interaction between the phase oscillation of stimulation and the endogenous oscillatory activity of the brain (Antal & Walter, 2013; Herrmann, Rach, Neuling, & Strüber, 2013; Paulus, 2011). The stimulation can be applied topographically using all the frequency bands that characterize the cortical rhythmic activity (delta δ, theta θ, alpha α, beta β and gamma γ) and, thus, serves as an effective tool for causally testing the correlational evidence of EEG studies and the related behavioural outcomes. Studies indicate that tACS may influence the membrane excitability of neuronal populations causing: (a) oscillatory entrainment and behavioural changes in a frequency-specific manner (Helfrich et al., 2014; Santarnecchi et al., 2013, 2016), (b) somatosensory and visual sensations (Feurra, Paulus, Walsh, & Kanai, 2011a; Kanai, Chaieb, Antal, Walsh, & Paulus, 2008; Schutter & Hortensius, 2010) and, iii) visuomotor coordination (Santarnecchi et al., 2017).

In this study, we explored and tested the causative role of MFΘ in modulating adaptive control during conflict monitoring and error processing. To this end, we applied tACS at different frequencies over the MFC of healthy participants while they performed a Flanker-like task where the choice to press a button in response to a central target letter (e.g. H or S) in a string of five is influenced by whether such letter is flanked by same (H and S) or different (S and H) letters. Given the conflict generated by the activation of response competition associated with the letters' arrangement, optimal performance in this task requires the integration of perceptual processing, response selection, action inhibition, and error monitoring. Using distinct frequency bands, we aimed at testing any specific role of MFΘ in the neural network underpinning conflict and error processing. We hypothesized that by delivering an oscillatory current at theta frequency over the MFC, the putative source of endogenous theta would modulate the response times needed to exert behavioural adjustment and control.

2 | MATERIALS AND METHODS

2.1 | Participants

Thirty-six healthy, right-handed participants (18 F; mean ± SD.; 24.42 ± 3.48) were tested in a Flanker-like task (Eriksen & Eriksen, 1974) while receiving tACS at different frequency bands. None of the participants reported a history of epilepsy, implanted metal devices, neurological or psychiatric diseases, and consumption of any medication. All participants had normal or corrected-to-normal visual acuity in both eyes and were naïve to the purposes of the study. The experimental protocol was approved by the ethics committee of the Fondazione Santa Lucia and was carried out in accordance with the ethical standards of the 2013 Declaration of Helsinki. All participants gave their written, informed consent to take part in the study and were paid 15€ for approximately one and a half hours of participation.

2.2 | Task

The task required participants to respond as accurately and as efficiently as possible to target letters (H or S) embedded in a string of distractor letters by pressing the corresponding button on a PC keyboard (the order of the two keys was counterbalanced across participants). Targets were flanked by two distractors on each side that could be the same or different with respect to the target. The four possible target-distractor combinations produced two congruent (HHHHH; SSSSS) conditions (CC) and two incongruent (HHSHH; SSHSS) conditions (IC). Due to the inherent target-distractor conflict, reaction times (RTs) were expected to be slower and the accuracy (Acc, rate of correct answers) was expected to be lower in IC than in CC (flanker effect). To make the task more challenging, the target stimuli were depicted in a white, green, or red colour (Fig. 1a). For each experimental block, participants were asked to mentally count the number of the coloured target letters while performing the Flanker (i.e.. "For this block, please count, mentally, only the green coloured target H"). At the end of each block, participants were invited to report the total number of the coloured stimuli presented during the block. The letter strings (visual angle of 8.17° horizontally and 1.63° vertically) appeared for 80 ms on a

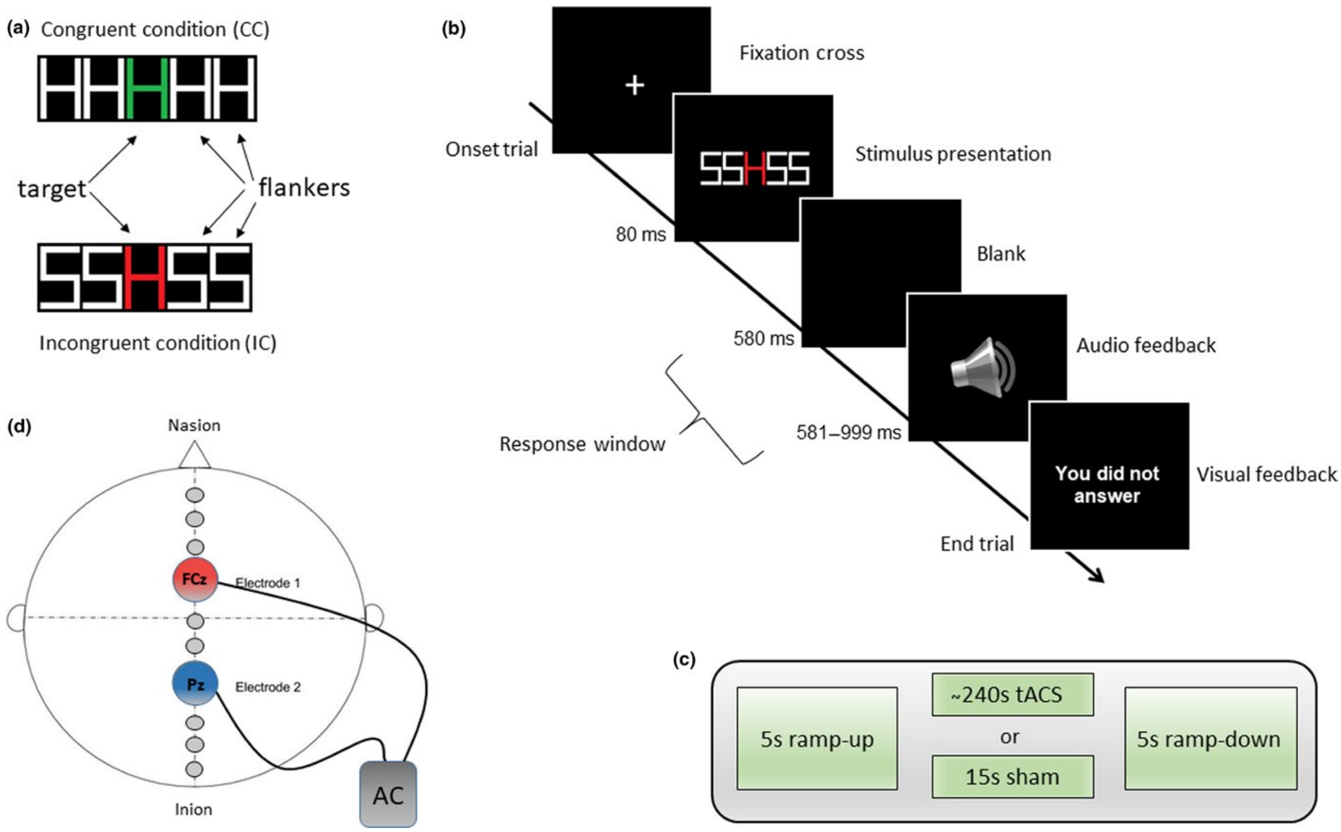

FIGURE 1 Example of congruent and incongruent stimuli (a) presented during the Flanker task. (b) Timeline of a single trial: a fixation cross appeared for 1000 ms at the beginning of the trial and was followed by 80 ms of stimulus presentation. The allowed response window was 920 ms, and if the response was not provided within 500 ms, an audio feedback (beeping sound) was delivered to stress participants to increase their speed. A visual feedback was presented on screen for 1000 ms in the case of a missed answer. (c) Block structure and period of stimulation or sham. (d) Electrodes' location for the transcranial alternating current stimulation. Electrode 1 ("active") was placed over FCz and Electrode 2 ("return") over Pz (10–20 International System). [Colour figure can be viewed at wileyonlinelibrary.com]

black screen of a 40.5 × 33 cm computer monitor and participants were asked to respond in a timeframe of 920 ms. A fixation cross was visible for 1000 ms between the presentation of each subsequent stimuli. In the trials where the response was not provided within 500 ms, a beeping sound (1000 Hz) delivered through a pair of headphones warned participants to answer more quickly in the subsequent trials. If participants failed to press the key during the available time, the visual feedback "*Non hai risposto*" ("You did not answer") appeared in the center of the screen (Fig. 1b). A training session of 40 trials (20 CC and 20 IC) was administered before the experimental phase. The task was developed through E-prime 2.0 software (Psychology Software Tools Inc., Sharping, PA, USA).

2.3 | Transcranial alternating current stimulation

The alternating current (AC) modulation was applied via two circular sponge-conductive-rubber electrodes (Sponstim, 25 cm^2, Neuroelectrics, Barcelona, Spain) soaked in a physiologic solution (NaCl). A rechargeable battery-operated stimulator system (Starstim/Enobio, Neuroelectrics, Barcelona, Spain) controlled by Bluetooth connection was used. The target 'active' electrode was placed over the MFC (FCz of the International 10–20 System) and the second 'return' electrode was placed over the medial parietal cortex (Pz of the International 10–20 System; Fig. 1d). This electrode arrangement was shown to successfully modulate frontal theta oscillations in healthy populations (Vosskuhl, Huster, & Herrmann, 2015). Both the electrodes were attached to the scalp through an EEG cap. To optimize the current flowing through the skin and scalp, the surface of the electrodes was coated with electro-conductive gel. The waveform of the current was sinusoidal without DC offset and 0° relative phase. The impedance was kept below 5kΩ.

tACS was applied during the task performance and, for each block, it was ramped up for the first 5s after which the task was followed by a 5s ramping down (Fig. 1c). The current intensity administered was set at 1500uA peak-to-peak. A frequency-dependent protocol was adopted (Feurra, et al., 2011b; Santarnecchi et al., 2013, 2017). Specifically, five different frequency tACS blocks - 2 Hz for the delta band (δ), 6 Hz for the theta band (θ, Cavanagh & Frank, 2014; Cohen, 2014), 11 Hz for the alpha band (α), 21 Hz for the beta band (β) and 60 Hz for the gamma band (γ) and a sham stimulation (<>) block - were delivered in a pseudo-random order. In addition to the sham, we decided to adopt a control frequency for each band in order to determine with more accuracy the specificity of the possible tACS effects applied in theta range in modulating top-down control during the Flanker. Sham stimulation lasted 15 s (5 s of ramp-up and 5 of AC) and then the AC was manually interrupted by the experimenter (5 s of ramp-down, Fig. 1c). This procedure was congenial to generate the same neurosensory perceptions of the real stimulation conditions over the participants' skin (Nitsche et al., 2008). The frequency adopted for the sham-tACS was the same as the previous stimulation block (i.e. III block: α -tACS frequency 11 Hz, IV block: <>-tACS frequency 11 Hz; I block: γ -tACS frequency 60 Hz, II block <>-tACS frequency 60 Hz, and so on).

2.4 | Procedure

Participants were invited to sit 70 cms away from the PC monitor in a quiet room and were asked to complete the Edinburgh Handedness Questionnaire (Oldfield, 1971), the form outlining the criteria for being included in neurostimulation studies (Rossi, Hallett, Rossini, & Pascual-Leone, 2009), along with three different scales; namely the *State-Trait Anxiety Inventory Form Y* (STAI-Y, the Trait scale, Spielberger, 2010), the *Behavioral Inhibition and Activation Scales* (BIS/BAS, Carver & White, 1994), and the 16-item reduced form of the *Need for Closure Scale* (NCC, Roets & Van Hiel, 2011). It is worth noting that previous studies reported how conflict and error monitoring could be influenced by affective processes such as motivational, trait-anxiety, and negative emotions (Amodio, Master, Yee, & Taylor, 2008).

After participants completed the surveys, their scalp was measured to localize the FCz and Pz positions of the International 10–20 System (respectively 10% in front and 20% behind the vertex Cz of the nasion-inion axis length). The areas of interest were cleaned with a cotton swab soaked in ethyl alcohol in order to reduce the skin's resistance and tracked with a marker. Finally, the two electrodes were fitted through an EEG-cap over the head of the participants and affixed with a Velcro belt.

To familiarize one's self with the device and set-up, a trial session of tACS was provided. Subsequently, participants were asked to relax and focus their attention on any sensation that could be felt (e.g. itching or burning) and/or seen (e.g. flashing or flickering) during tACS. The stimulation lasted 15 s (5s ramp-up, 5s AC, and 5s ramp-down) and was set at 750uA intensity and 13 Hz frequency.

Following this phase, the task was introduced and the training session commenced. In the experimental phase, we turned off the lighting in the room. For each block, 108 stimuli (54 CC and 54 IC) were randomly presented at the center of the PC monitor in correspondence to the fixation cross. Participants performed in six different blocks, each of which lasted ~240s, with an inter-block interval of ~300s (total number of trials 648).

Finally, at the end of each stimulation block, we asked participants to report any tACS-induced discomfort and any sensation that might have occurred in the block. In this regard, it has been previously reported that, during electrical brain modulation, some sensorial, perceptual, and physical effects might arise due to the current propagation within the scalp, skin, retina, and nerves (Fertonani, Ferrari, & Miniussi, 2015). In light of this, participants were required to assess sensations along a 0–100 scale (0 = no sensation at all − 100 = max sensation perceived) of the following categories: *Somatosensory* (i.e. the skin sensations perceived under the electrodes area such as itching, heating, tingling, burning, and prickling); *Visual* (i.e. the perceptual phenomena appearing in the central or peripheral visual field like flickering and the presence of flashes and/or bright dots); *Taste* (i.e. the metallic sensation in the mouth); and *Other sensations* (i.e. body and vestibular-related sensations like fatigue, dizziness, head heaviness, nausea, headache, and/or sleepiness).

2.5 | Data analysis

Statistical analyses were performed in the R environment for statistical computing (R Development Core Team, 2017) using the *lme4* package (Bates, Maechler, Bolker, & Walker, 2014). *p*-values and degrees of freedom were computed through the Kenward-Roger approximation. This statistical methodology has been used in neuroscience and psychology research by others (i.e., Rahnev, Nee, Riddle, Larson, & D'Esposito, 2016) and our own research groups (Ponsi, Panasiti, Scandola, & Aglioti, 2016).

Reaction times (RTs in ms) on the correct trials and speed-accuracy tradeoff (SAT) were analyzed using linear mixed models for a 6 × 2 factorial design with Frequency (δ, θ, α, β, γ, <>) and Condition (congruent vs. incongruent) as fixed factors. SAT (RTs/Acc) has been commonly described as a function of the covariation between response speed (RTs) and accuracy (Acc) reflecting strategic preferences in time-forced decision tasks (Heitz & Schall, 2012). Therefore, in this study, we asked the participants to be as rapid and accurate as possible so that the SAT could express an individual index of the general performance (i.e. poor performance: fast RTs/low Acc vs. good performance fast RTs/high Acc). As random effects, we considered a random intercept and the random slopes for Condition and Frequency for each participant in order to take into account the within-subjects noise. Furthermore, the plausible effects of fatigue were treated considering, as random, an intercept for each level of Order. In an "lme4-like syntax" the model was: *SAT (or RT) ~Frequency*Condition+(1 + Condition+Frequency|Participant)+(1|Order)*.

The accuracy (i.e. number of correct responses) was analyzed by means of a logit mixed model for binomial dependent variables where 0 referred to errors and 1 to correct responses. We used, as fixed factors, the Frequency and the Condition, and the intercept of the Participant as random factor. For the post-error slowing (PES), we used, as fixed effects, the Frequency, the Condition post-error (CPost: congruent vs. incongruent), and their interaction. As random effects we used an intercept and the order of the block to capture fatigue-related noise for each level of Frequency, and an intercept and the slopes for CPost, Frequency, and the number of errors in z-scores for each Participant. In an "lme4-like syntax" the model was: *PES ~Frequency*Condition+(1 + Condition+ z(Errors)|Participant)+(1 + Order|Frequency)*. The selection of the random effects was done in order to take into account the whole within-subjects variability and the possible effects of the number of errors and fatigue. Because this analysis is crucial for this study, we also computed the bootstrapped *p*-values of each effect with 5000 iterations to confirm significant results. Note that bootstrap analysis is recommended to demonstrate the robustness of the findings obtained with linear mixed effect models (Efron & Tibshirani, 1994).

For each participant, outlier values were removed from the entire dataset through the interquartile rule. The subjective effects induced by the stimulation in the different bands were analyzed through repeated measure ANOVAs with sphericity correction considering Frequency and Secondary Effects as factors. The type of sensations (Sub-Category factor) included Visual, Cutaneous, Taste, and Others as levels. Then, for each category, additional ANOVAs with sphericity correction were conducted taking into consideration their sub-categories (*Visual*: Flash, Bright dots, Flickering; *Somatosensory*: Itching, Tingling, Prickling, Heat, Burning; *Other Sensations*: Fatigue, Dizziness, Heaviness, Headache, Sleepiness, Nausea). The Taste sensations were close to zero and, in turn, were not analyzed.

Further, we performed covariation analyses (ANCOVAs) in order to test possible associations between the performance variables (i.e. RTs, Acc, SAT), the tACS-induced secondary effects, and the scores obtained from the personality questionnaires. Covariation analyses were conducted by means of linear mixed models (RTs, SAT) or logit mixed models (Acc) with the abovementioned Fixed and Random effects, adding the covariates of interest among the Fixed effects. For each performance variable, we covaried the impact of personality scores and the impact of tACS-induced sensations in separate analyses. Personality scores and tACS-induced sensations were scaled in a -1;1 range in order to have zero- centered covariates and avoid spurious results. Post-hoc comparisons were performed using the Bonferroni and Tukey correction for multiple comparisons.

Since our hypothesis was mainly related to the effect of θ-tACS in modulating the response times needed to exert behavioural adjustment and control, we have reported the results of Acc, SAT and tACS-induced sensations in the Supporting Information.

3 | RESULTS

3.1 | Reaction times

Data was normally distributed (kurtosis = 0.23; skewness = 0.76). The analysis showed a main effect of Condition ($F_{1,209.9} = 110.74$; $p < 0.001$) with faster responses to congruent (435.78 ± 49.41) vs. incongruent (466.47 ± 48.46) stimuli (please see the Fig. S1 for the data plot). The main effect of Frequency ($F_{5,37.682} = 0.806$; $p > 0.05$) and the interaction Frequency x Condition ($F_{5,175.000} = 1.043$; $p > 0.05$) were not significant. Furthermore, a main effect of the tACS-induced sensations ($F_{1,117.17} = 4.399$; $p < 0.05$) as a covariate emerged from the covariance analysis. In particular, the higher the participants evaluated the effect of the tACS-induced sensation, the faster the RTs. This relation did not depend on the Frequency ($F_{5,40.423} = 1.093$; $p > 0.05$) of tACS. No other covariates reached levels of significance (all $p > 0.05$). The whole model had a mean squared error (MSE) = 8.09, marginal $R^2 = 0.08$ and a conditional $R^2 = 0.96$.

3.2 | Post-error slowing

We calculated the PES index by means of the following formula:

$$PES = MRT_{post-error} - MRT_{post-correct}$$

where MRTpost-error is the mean of the reaction times of correct trials after errors and MRTpost−correct is the mean of the reaction times in post-correct trials (Danielmeier & Ullsperger, 2011). Data was normally distributed (kurtosis = 0.13; skewness = 0.08). The analysis showed a main effect of CPost ($F_{1,353} = 7.482$; $p = 0.006$; $p_{bootstrapped} < 0.001$) whereby participants were faster in congruent (8.38 ± 72.4) rather than in incongruent (37.43 ± 71.51) stimulus combination after errors. A significant interaction Frequency × CPost ($F_{1,1979.67} = 2.562$; $p = 0.026$; $P_{bootstrapped} = 0.025$) emerged in the linear mixed model. In particular, the Bonferroni post-hoc revealed a significant difference between θ-tACS (3.07 ± 42.18) and sham (22 ± 34.8; $p = 0.042$) in response to congruent stimuli following errors (Fig. 2). More importantly, the differences between sham and the other frequencies did not reach statistical significance (sham vs. δ: $p = 0.111$; α: $p = 0.248$; β: $p = 0.323$; γ: $p = 0.164$). No effect for Frequency was significant ($F_{5,2152.19} = 1.932$; $p > 0.05$). Additional analysis by means of a logit mixed model computed on the accuracy following errors showed a main effect for Condition ($\chi^2_{(1)} = 5.06$; $p = 0.024$). Results revealed that participants were more accurate in responding to congruent (0.92 ± 0.13) compared to incongruent (0.88 ± 0.16) post-error stimuli. Marginal $R^2 = 0.15$ and conditional $R^2 = 0.56$. No covariance effects reached statistical significance ($p > 0.05$).

Finally, although the difference with the sham condition was not significant, data inspection seems to suggest that β-tACS modulated post-errors slowing through reducing the time to respond to congruent stimuli following error execution as it happened during θ-tACS. To test whether such an effect may also be related to β-tACS, we removed from the linear mixed model the theta frequency. The analysis showed that by removing this condition, the CPost effect was still significant ($F_{1,28.9} = 31.5$; $p = 0.001$) while the Frequency main effect ($F_{4,24.896} = 0.955$; $p = 0.449$) and their interaction ($F_{4,24.362} = 0.95$; $p = 0.452$) were not.

3.3 | Personality Questionnaire

Data collected through the questionnaires (STAI-Y, BIS/BAS, NCC) were used as covariates in order to measure any possible relation between the dependent variables of the task

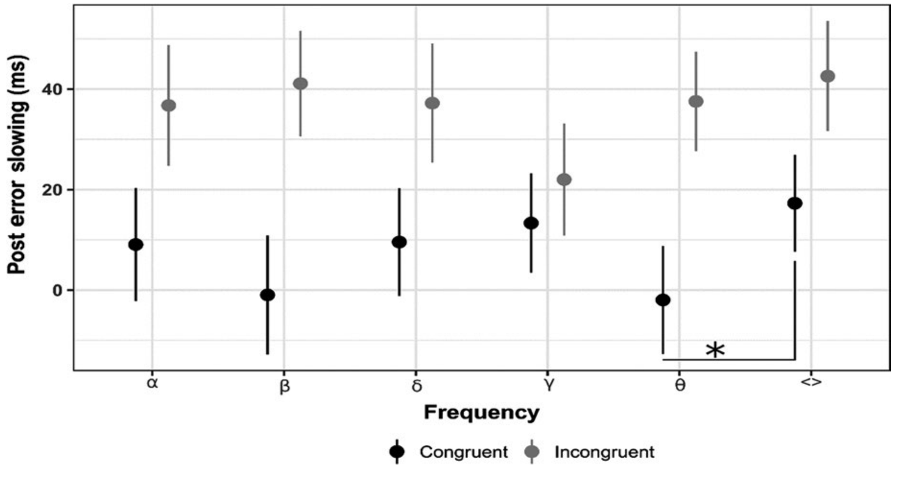

FIGURE 2 Main effect of the difference between theta (θ) -tACS and sham in the post-error slowing (PES) for congruent stimuli following errors (Bonferroni post-hoc correction: $p = 0.042$). Delta δ, Alpha α, Beta β and Gamma γ did not differ from the sham condition (all $p > 0.1$)

(RTs, Acc, SAT, PES) and individual personality traits. The analysis showed no effects for any of the aforementioned factors (all $p > 0.05$, see Table 1).

4 | DISCUSSION

In this study, we applied band-specific transcranial Alternating Current Stimulation (tACS) over the medial frontal cortex (MFC) to explore the interaction of exogenous frequency bands with task-related endogenous band-specific activity. By expanding on studies that applied θ-tACS over the frontal cortex to modulate endogenous oscillations (Sela, Kilim, & Lavidor, 2012; van Driel, Sligte, Linders, Elport, & Cohen, 2015; Vosskuhl et al., 2015; Wischnewski, Zerr, & Schutter, 2016), we have been able to show, for the first time, a difference in the post-error slowing (PES) when participants received external electrical current in the theta frequency compared to the sham condition. Specifically, θ-tACS allowed participants to preserve the response threshold increment (i.e. reduced post-error slowing) after error execution in the congruent condition in the presence of the same level of accuracy at baseline (sham). Most importantly, the transcranial application of alternating current did not significantly affect any other behavioural performance (i.e. RTs, Acc and SAT) in a frequency dependent manner. This result may highlight the specificity of θ-tACS in modulating behavioural adjustment.

Moreover, in order to test the influence of tACS-induced secondary effects on behaviour, we collected the subjective experience of physical sensations elicited during the stimulation. Both α-and β-tACS elicited more intense visual and somatosensory phenomena with respect to the other frequencies. Although a general inverse association emerged between reaction times and the scores provided by the participants, these sensations did not impact the Flanker performance at all.

TABLE 1 *p*-values of the covariance analyses between the dependent variables of the performance (reaction times RTs, accuracy Acc, speed-accuracy tradeoff SAT, post- error slowing PES) and the subjective scores of the personality questionnaires (*State-Trait Anxiety InventoryForm Y,* STAI-Y; *Behavioral Inhibition and Activation Scales*, BIS/BAS; *Need for Closure Scale*, NCC)

	Personality Questionnaires		
Performance variable	**BISBAS**	**STAI**	**NCC**
RTs	$p = 0.609$	$p = 0.632$	$p = 0.789$
Acc	$p = 0.415$	$p = 0.570$	$p = 0.640$
Tradeoff	$p = 0.435$	$p = 0.988$	$p = 0.838$
PES	$p = 0.277$	$p = 0.283$	$p = 0.199$

4.1 | Electocortical signatures of performance monitoring

Electroencephalic (EEG) studies suggest that neuro-electrical signatures in the time and time-frequency domains index error and conflict monitoring (Pavone et al., 2016; Pezzetta, Nicolardi, Tidoni, & Aglioti, 2018; Spinelli, Tieri, Pavone, & Aglioti, 2018). Error Related Negativity (ERN; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993) is an event related potential evoked when people perform or observe an error (Pavone et al., 2016; Spinelli et al., 2018) and is partly associated with behavioural adjustment (for a review see Gehring, Liu, Orr, & Carp, 2012). The same process also seems to be indexed by a specific spectral signature in the theta band; a frequency activity recorded along the frontal midline that correlates with the need for enhanced cognitive control (Cohen & Donner, 2013; Luu et al., 2004; Trujillo & Allen, 2007). So far, EEG studies have provided only correlational evidence that MFΘ may be a marker of error and conflict monitoring (Nigbur et al., 2011; Vissers, Ridderinkhof, Cohen, & Slagter, 2018). However, it is not completely clear whether MFΘ is causally associated with the representational stimulus-response mismatch, the communication level of oscillatory signals among brain areas, or solely with the implementation of behavioural adaptation (Cavanagh & Frank, 2014; Cohen, 2014). An initial attempt to solve this issue was provided by van Driel et al. (2015) who administered tACS at the individual theta frequency over the MFC of healthy participants while they were required to perform a Simon task. By analyzing the congruency sequence effect, a measure associated with behavioural adjustments, these authors found a slowed response mode in low conflict trials when theta, rather than alpha stimulation, was applied. Thus, midfrontal theta involvement in conflict processing may have led to a more precautionary approach resulting in slower RTs during conflict adaptation (van Driel et al., 2015). Expanding on this study, we tested the hypothesis of a change in conflict and error processing in a Flanker-like task by delivering exogenous 6 Hz theta stimulation on the MFC. The results did not show a general influence of tACS on the conflict monitoring, but a specific modulation of θ-tACS on the post-error slowing computation. In fact, participants showed a shorter PES during theta stimulation compared to the sham condition for the congruent stimuli that followed errors. This effect may lead to a less conservative response mode. The discrepancy between our results and those shown by van Driel et al. (2015) may rely on some methodological and conceptual differences that warrant further discussion. First, although both measures reflect adaptive control, the "congruency sequence effect" may index conflict-driven adaptation mechanisms (Gratton, Coles, & Donchin, 1992). In contrast, "post-error slowing" is a behavioural marker of error-driven adjustments (Rabbitt &

Rogers, 1977). Thus, the two indexes may underlie distinct neural and behavioural mechanisms in information coding (Notebaert & Verguts, 2011). Second, the administration of different tasks (Simon vs. Flanker), the choice of different electrodes' size and their arrangement, and/or the physical parameter of the administered alternating current (i.e. frequency and amplitude) may lead to a different influence on the targeted cortical networks and to a different pattern of outcomes. Tellingly, rather than being mutually exclusive, the results of the two studies may be considered complementary and useful to understand the causative role of frontal theta oscillations in exerting top-down behavioural adjustment and modulating adaptive control. It is worth noting that, following the monitoring conflict account of Botvinick et al. (2001), the post-error slowing is the adaptive mechanism indexed by behavioural adjustments in forced-choice decision tasks that may facilitate top-down control (Botvinick et al., 2001; Danielmeier & Ullsperger, 2011). In the same vein, Cavanagh and Shackman (2015) conducted a meta-analysis where they reported how the amount of MFΘ could predict the level of behavioural slowing after error execution; specifically, the larger error-related MFΘ signals, the higher the post error slowing (Cavanagh & Shackman, 2015). However, in our study, we found that θ-tACS compared to sham caused a reduced post-error slowing without determining speed-accuracy tradeoff through the increase of error responses. Interestingly, a recent EEG study (Valadez & Simons, 2018) showed a correlative link between MFΘ and PES during the Flanker performance. In particular, greater MFΘ power following error-trials was associated with less behavioural slowing. This result may confirm the functional role of midline frontal oscillations in behavioural adjustments (Valadez & Simons, 2018).

We speculate that the above modulation may have affected the neuronal communication across the cortical nodes recruited for signaling the request of adaptive control thereby making the transmission faster and, therefore, more efficient. In this respect, although behavioural improvements were reported during online and offline θ-tACS protocols (Jaušovec, Jaušovec, & Pahor, 2014; Pahor & Jaušovec, 2014; Vosskuhl et al., 2015; Wischnewski et al., 2016), the underlying neurophysiological mechanisms associated with the modulation of neuronal oscillatory activity remains controversial. In two studies, for example, it has been reported that after θ-tACS, the performance in fluid intelligence (Pahor & Jaušovec, 2014) and working memory (Vosskuhl et al., 2015) tasks improved and was accompanied respectively by spectral power and amplitude increment in the theta range. Conversely, Chander et al. (2016) showed that applying tACS at individual theta frequency over the medial frontoparietal network (one electrode at Fpz location and the second at Pz) interacted with the endogenous MFΘ phase reducing its power and worsening the performance in a n-back task (Chander et al., 2016). Moreover, due to the bicephalic montage of electrodes adopted in the present study, we cannot exclude that the administration of alternating current in theta band may have affected the activity of neuronal populations placed within the medial parietal cortex that are involved in other cognitive processes or in the interregional communication within the frontoparietal network (Vissers et al., 2018). Indeed, studies have reported that, after performing or observing an error, a positive event-related potential linked with error awareness - the so-called Positivity Error (Pe; Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Overbeek, Nieuwenhuis, & Ridderinkhof, 2005; Panasiti, Pavone, & Aglioti, 2016) - peaks over the centro-parietal electrode (Pz). This electrocortical component seems to be associated with tardive error processing and post-error strategy compensation (Hajcak, McDonald, & Simons, 2003; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001). Recently, a reduced latency of Pe has been shown when participants perform behavioural correction (faster RTs) following errors during the resolution of a Flanker task with human faces as targets and distractors (Navarro-Cebrian, Knight, & Kayser, 2016). Therefore, a secondary speculative interpretation might be that the error monitoring may have been affected by θ-tACS through the modulation of the functional frontopartietal connectivity causing anomalous signal processing between cortical nodes engaged in post-error adjustment, and thus, altering the temporal slowing after error execution. It is worth noting that, following 10 min of bilateral θ-tACS of the dorsolateral prefrontal cortex, this cortical hub decreased nodal efficiency (i.e. the ability to efficiently exchange information with other neural structures) and the capability to functionally integrate with other brain regions (Onoda, Kawagoe, Zheng, & Yamaguchi, 2017). However, such after-effects were tested during resting state fMRI and further studies are needed to verify whether similar changes also occur during other cognitive performances. An interesting methodological approach could be the administration of theta phase and anti-phase stimulation between FCz and Pz which may provide a useful strategy to synchronize or desynchronize, respectively, the local neuronal communication (Polanía, Nitsche, Korman, Batsikadze, & Paulus, 2012).

Finally, the absence of simultaneous or post-stimulation co-registration with EEG/MEG represents a limitation of the present study that prevents us from making clear inferences about any specific neurophysiological mechanism underlying the θ-tACS effectiveness in modulating endogenous activity in the theta range (i.e. oscillatory entrainment; Thut, Schyns, & Gross, 2011; Reato, Rahman, Bikson, & Parra, 2013). In turn, showing correlations between behavioural outcomes and electrocortical signals may be the optimal way to plan tACS experiments (Antal & Herrmann, 2016) and future investigations using an EEG/online tACS approach should be adopted to reveal the clear mechanisms of phase locking effects.

4.2 | Subjective reports of feelings induced by specific frequency band stimulation

The transcranial application of electric current can induce secondary effects depending mainly on the physical parameters (e.g. frequency) or methodological differences (e.g. electrode size). Although conspicuous (i.e. cutaneous discomfort or visual distortions) and potentially confound-inducing effects may be generated (i.e. creation of perceptual bias; Fertonani et al., 2015), little attention has been paid to these phenomena thus far. For example, note the study in tACS at θ, α, β and γ range that was delivered over the visual cortex to explore the presence/absence and the strength of the phosphenes under conditions of light or darkness (Kanai et al., 2008). It appeared that α-tACS and β-tACS evoked most intense phosphenes in dark and light conditions respectively. Crucially, however, a subsequent study using a similar paradigm seems to demonstrate that the effects were related to the frontalis-vertex electrodes arrangement that caused a passage of the current in the retina rather than to the modulation of the primary visual cortex (Schutter & Hortensius, 2010).

In our study, we found that α-and β-tACS elicited more sensorial phenomena with respect to the other frequencies in a condition where the light in the room was reduced. This may hint at the critical issue of applying such bands for frontal cortex modulation in paradigms where time-constrained stimulus-response sequences require visual processing and high accuracy. Nevertheless, our results clearly showed that the behavioural changes affected by θ-tACS did not depend on the secondary sensorial effects.

5 | CONCLUSION

By delivering alternating current in theta band over the MFC in participants performing a choice task where errors were induced by elements of conflict, we have been able to demonstrate a reduction in the post-error slowing without any significant increase of errors. The behavioural modulation induced by band specific exogenous currents paves the way for future applications of frontal θ-tACS for restoring oscillatory patterns that may be dysfunctional in conditions of impaired cognitive control (e.g. in Parkinson's Disease or in pathological gambling).

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CONFLICT OF INTEREST

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

DATA ACCESSIBILITY

The present data will be made publicly available upon request and will be stored at the Department of Psychology, Sapienza University, Rome.

AUTHORS CONTRIBUTION

GF and SMA designed the study. GF recorded the data. GF and MS analyzed the data. GF, MS, MF, EFP, SR and SMA discussed the results. GF, MS, and SMA drafted the manuscript.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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