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# HD-tDCS improves conflict processing and general behavioral stability

Ronghan Liu, Miao Wang, Qiang Liu, Xiujuan Jing, Qiang Hao, Hang Yu & Yifeng Wang✉

**Transcranial Direct Current Stimulation (tDCS) has been employed to enhance executive control (EC), thereby improving cognitive functions and mental health. However, the effects of tDCS on EC remain inconclusive, and the mechanisms involved in its impact on baseline and conflict processing are not well understood. This study applied high-definition tDCS (HD-tDCS) to the left dorsolateral prefrontal cortex DLPFC) to investigate the distinct effects of tDCS on baseline and conflict processing. Compared to the sham group, tDCS significantly reduced reaction time variability in both conditions and decreased mean reaction time and error rate in the conflict condition. These findings demonstrate significant enhancements in general behavioral stability and conflict processing respectively. This study demonstrates a significant enhancement of tDCS on EC, elucidating the dual mechanisms of tDCS in modulating the baseline state and EC, providing valuable insights into the mechanisms of tDCS intervention on cognitive functions.**

**Keywords** HD-tDCS, Executive control, Left DLPFC, Steady-state block design

Executive control (EC) involves monitoring and resolving conflicts among expectations, stimuli, and responses[1]. It flexibly adjusts behaviors to meet task demands, encompassing goal maintenance, conflict resolution, error detection, and curiosity[2,3]. EC is integral to working memory, executive functions, language processing, and attention[4–7]. Impairments in EC are evident in various behavioral and mental disorders, such as Attention Deficit Hyperactivity Disorder (ADHD), Major Depressive Disorder (MDD), and Autism Spectrum Disorder (ASD).

In summary, EC plays a vital role in cognitive processing and mental health. Researchers have adopted various approaches to enhance EC, including physical exercise, mindfulness meditation training, cognitive training, and physical stimulation methods[8–13]. Advances in technology have allowed for the direct stimulation of specific brain regions through non-invasive brain stimulation methods, such as Transcranial Direct Current Stimulation (tDCS). tDCS is showing promise in cognitive enhancement and in the treatment of neuropsychiatric disorders, specifically dysexecutive syndromes[14–16].

The application of tDCS to the dorsolateral prefrontal cortex (DLPFC) for EC intervention has yielded varied outcomes. Some studies have shown improvements in EC[17–21], while others have reported no significant effects[22–26]. The inconsistency in findings is often attributed to variations in stimulation parameters (e.g., stimulation technique, electrode size, and current intensity) and the state of participants[17,27–30]. A meta-analysis suggested that utilizing small electrodes and high current density yielded a greater positive effect on EC[22]. Furthermore, HD-tDCS offers superior spatial precision and the ability to regulate cognitive activity in a region-specific manner, avoiding confounding effects seen with conventional tDCS. This is because conventional tDCS employs larger electrodes that may stimulate two brain regions simultaneously, resulting in widespread stimulation that impacts areas between the active and reference electrodes, potentially complicating the interpretation of the neural processes involved in cognitive function[28,31]. Recent studies have shown that the effects of tDCS are contingent on individuals' cognitive baseline prior to stimulation[30,32]. For example, Dubreuil-Vall et al. reported that participants with poorer executive function performance at baseline showed greater improvements after tDCS[18].

However, few studies have attributed these uncertain outcomes to cognitive activity itself. In the Flanker paradigm, EC is quantified by comparing performance differences between incongruent and congruent conditions, known as the conflict effect[33]. This means that any changes in performance in one condition can affect the measurement of EC, leading to mixed intervention effects. Most research has focused on how tDCS modulates the conflict effect, particularly in incongruent tasks. Some studies have indicated tDCS's ability to

Institute of Brain and Psychological Sciences, Sichuan Normal University, No.5, Jing'an Road, Chengdu 610066, China. ✉email: wyf@sicnu.edu.cn

reduce reaction times (RTs) in congruent tasks[21,34]. The differential effects of tDCS on congruent and incongruent conditions may underlie the instability of its effects on EC.

Studies employing event-related designs in the Flanker task have faced two main challenges. First, presenting congruent and incongruent trials randomly has shown to reduce the conflict effect after incongruent trials and increase it after congruent trials, known as the congruency sequence effect (CSE)[35,36]. Recent research has revealed that tDCS targeting the DLPFC can lead to longer RTs for incongruent trials following congruent ones or a smaller conflict effect after incongruent trials[37,38]. This complexity obscures the mechanisms behind the intervention for conflict effects, hampering clear conclusions. Furthermore, the reliability of previous EC tests has been insufficient, with split-half reliability scores below 0.8, highlighting the need for improvement[39–42].

To address these issues, we employed a revised Flanker task to separate congruent and incongruent conditions. The task was conducted with a steady-state block design and has been demonstrated to be highly reliable in assessing EC[43–45]. The left DLPFC, the most common target in past studies for enhancing cognitive functions, has also been found to be a target for intervening in executive function and EC, making it the selected target for this study[17,18,46,47]. HD-tDCS was utilized for its improved spatial precision and to avoid confounding effects associated with conventional tDCS[28,31]. These procedures successfully separated two conditions, facilitating the assessment of intervention mechanisms on baseline state and conflict processing respectively.

## Materials and methods

### Ethical approval

The prospective, parallel randomized controlled trial received approval from the Institutional Review Board of Sichuan Normal University (SCNU-211206). The research was conducted in strict adherence to the Declaration of Helsinki principles. All procedures were carried out in compliance with relevant guidelines and regulations. Informed consent was secured from all participants.

### Participants

A total of 50 healthy undergraduates from Sichuan Normal University were involved in this study. Of these, 25 students (aged 18 to 24 years, mean age 20.84, 7 males, 18 females, all right-handed) participated in the left DLPFC tDCS experiment, while another 25 volunteers (aged 18 to 25 years, mean age 20.8, 6 males, 19 females, all right-handed) underwent the sham experiments, as the control group. They had no history of neurological or psychiatric disorders, maintained normal or corrected-to-normal vision, and abstained from alcohol or caffeine for 24 h prior to testing. Additionally, none of the participants had previously participated in similar experiments. There were no significant differences in age ($t(48) = 0.064$, $p = 0.949$) or gender ($\chi 2 = 0.104$, $p = 0.747$) distribution between the two groups. Informed consent was obtained from all participants, and the study was approved by the local ethics committee of Sichuan Normal University.

### HD-tDCS

The study utilized a high-definition 64-channel transcranial direct current stimulation system (NeuStim NSS14, Neuracle, Changzhou, China). A total current of 1 mA was applied for 20 min during tDCS sessions, with five source electrodes positioned on the left DLPFC to achieve peak current density at F3 based on the 10–20 EEG system. The participants were blinded to the type of tDCS. The current ramp-up and ramp-down times at the start and end of the stimulation were both set to 15 s. In the sham condition, the electrodes were placed at the same positions but the current was applied only for the 15-s ramp-up phase at the beginning and the end of a 20-min sham-stimulation period. These parameters were chosen based on previous reports that bodily sensations and real stimulation did not show significant differences, but did not have a sustained effect on cortical activity[17,18,48,49].

### Procedure

Participants were randomly assigned to either the tDCS group or the sham group. Each participant underwent two sessions for the experimental tasks: baseline and conflict. Task sequencing was counterbalanced using the ABBA method, with a 72-hour gap between sessions. Prior to each task, the tDCS group received 10 min of stimulation, followed by concurrent stimulation during the task for another 10 min. The sham group underwent a similar procedure, albeit without real stimulation. Following task completion, participants filled out a somatic symptom questionnaire. Procedure details and questionnaire are shown in Fig. 1 and Supplementary Table 1.

### Task and stimuli

Stimuli were presented using E-Prime 2.0.10 on a 14-inch monitor. Participants fixated on the screen at a fixed distance of 60 centimeters. The Flanker task utilized a steady-state block design. Congruent and incongruent conditions were presented in separate blocks, with tasks administered at a fixed frequency of 0.5 Hz. Each trial commenced with a 500 ms blank screen, followed by the simultaneous display of the target and flankers until the participant's response within a maximum duration of 1500 ms. Post-response, the stimuli vanished, and a blank screen appeared for 1500 ms minus the RT before the subsequent trial initiation. Each trial had a duration of 2 s, with a total of 300 trials per condition (Fig. 1).

### Statistical analysis

We performed distributional tests for EC scores, RTs, RT standard deviation, and accuracy. After applying the Shapiro-Wilk normality test, we found that some data did not have a normal distribution. The findings are illustrated in Supplementary Tables 3–6.

The conflict effect is assessed through EC scores, derived from the difference between the mean RT or accuracy of incongruent and congruent conditions. A lower EC score signifies enhanced EC proficiency[33]. If

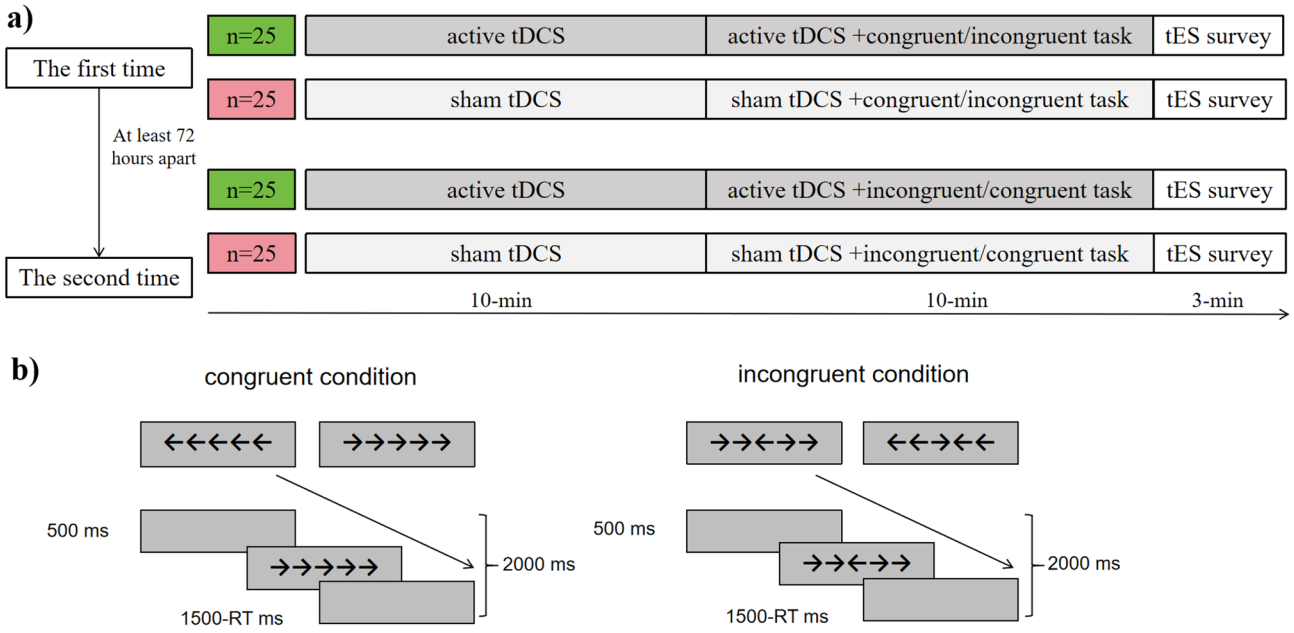



**Fig. 1**. Experimental procedure. (a) Participants underwent two separate sessions for the baseline and conflict tasks, with a minimum 72-hour interval between sessions. Each session consisted of 10 min of active stimulation or sham, followed by 10 min of task performance with concurrent stimulation or sham. Participants completed a somatic sensation questionnaire immediately after task completion. (b) The Flanker task in a steady-state block design includes congruent and incongruent conditions blocks. In the Flanker task, subjects must attend and respond to the direction of a central arrow that is surrounded ("flanked") by distracting stimuli. Trials are classified as congruent, in which the central arrow points to the same direction as the flanker arrows, and incongruent trials, in which the central arrow points to the opposite direction of the flanker arrows. Participants are instructed to press the left or right arrow buttons depending on the direction to which the central arrow is pointing, ignoring the flanker arrows.

data satisfied a normal distribution, an independent sample t-test would be performed to assess the between-group difference, otherwise, a Mann-Whitney U test a would be performed.

RTSD was log-transformed for a 2 × 2 mixed-model ANOVA. RT of single trials was then analyzed using a Generalized Linear Mixed Model (GLMM) with a Gamma distribution. Accuracy was also analyzed using GLMM with a binomial distribution. Post-hoc comparisons for significant effects were conducted using Bonferroni correction for p-values.

The self-written script of Matlab R2022b was employed for reliability analysis. Split-half reliability is a commonly used method to assess the reliability of cognitive tasks[43,50]. The random sampling method can help to reduce sampling error, and the average reliability coefficient from a large number of random sampling instances (more than 5000 times) is similar to test-retest reliability[51–53]. In our study, split-half reliability was calculated as follows: trials for each condition were randomly split into two halves, EC scores or RT were calculated for each half, Pearson's correlation was conducted across subjects for the scores, these steps were repeated 10,000 times, and the split-half reliability was determined by averaging the 10,000 correlation coefficients. Interpretation of reliability indices: values below 0.70 are considered problematic, those between 0.70 and 0.80 are deemed borderline, and values exceeding 0.80 are considered acceptable[54].

The side effects of electrical stimulation were compared using a Wilcoxon signed rank test for within-group analysis and a Mann-Whitney U test for between-group analysis.

## Result

### HD-tDCS reduces conflict effects

An independent samples t-test revealed that, compared to sham stimulation, tDCS significantly reduced the EC scores for RT (the difference in RT between incongruent and congruent trials, t (48) = -2.035, $p = 0.047$, Cohen's d = -0.576).

Given that the EC scores for accuracy did not conform to a normal distribution, a Mann-Whitney U test was utilized. The result revealed that, compared to sham stimulation, tDCS significantly increased the EC scores for accuracy (the difference in accuracy between incongruent and congruent trials (U = 149, $p = 0.001$, $r$= -0.523). The results are presented in Fig. 2.

### HD-tDCS promotes behavioral stability

A 2 × 2 mixed-model ANOVA on RTSD showed a significant main effect of congruency (F (1, 48) = 25.108, $p < 0.001$, $\eta^2 p = 0.343$). Post-hoc analysis indicated that RTSD for the congruent task was significantly lower

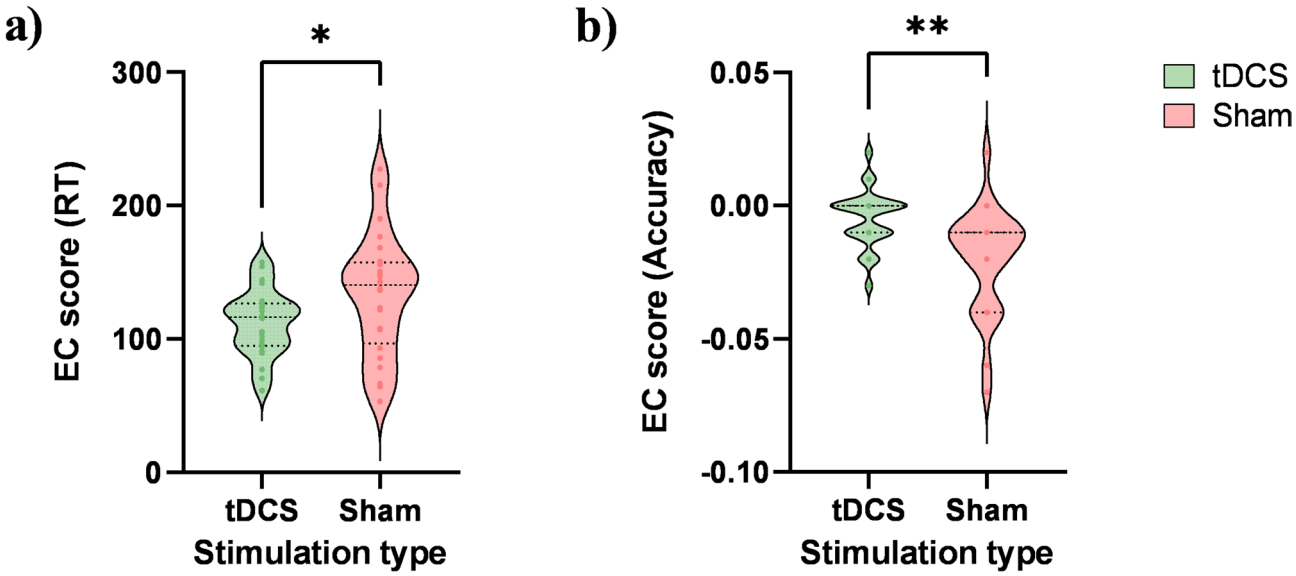



**Fig. 2**. HD-tDCS Reduce Conflict Effects. a) the difference in EC score (incongruent RT-congruent RT) between HD-tDCS and sham conditions; b) the difference in EC score (incongruent ACC-congruent ACC) between HD-tDCS and sham conditions. *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

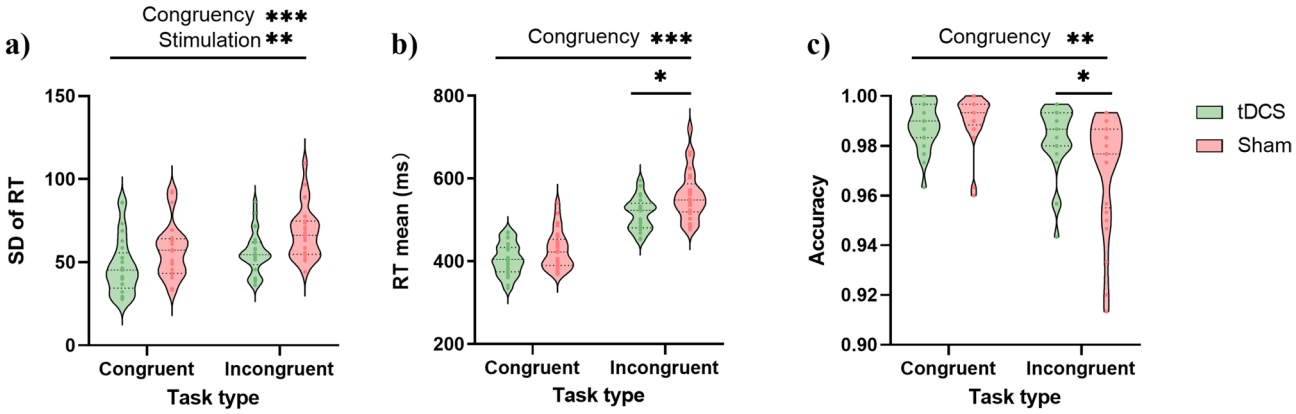



**Fig. 3**. The different mechanisms by which HD-tDCS improves baseline and conflict processing include: a) HD-tDCS significantly reduced the standard deviation of RTs in both congruent and incongruent conditions; b) HD-tDCS significantly decreased RTs in the incongruent condition; and c) HD-tDCS significantly improved accuracy in the incongruent condition. *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

than for the incongruent task (t (48) = -5.011, $p_{(bonf)} < 0.001$, Cohen's d = -0.695). Furthermore, a main effect of stimulation was observed (F (1, 48) = 9.333, $p = 0.004$, $\eta^2 p = 0.163$), showing that RTSD in the tDCS condition was significantly lower than in the sham condition (t (48) = -3.055, $p_{(bonf)} = 0.004$, Cohen's d = -0.753). However, no significant interaction between congruency and stimulation condition was found. Please refer to Fig. 3 for detailed results.

## HD-tDCS enhances efficiency in conflict processing

The results of the GLMM showed that RT for the incongruent task was significantly longer than for the congruent task ($\beta = 0.244$, CI = [0.240, 0.248], $p < 0.001$) and a significant congruency × stimulation interaction ($\beta = 0.026$, CI = [0.020, 0.031], $p < 0.001$). After post-hoc tests and corrections, the results indicated that tDCS significantly reduced RT for the incongruent task only ($\beta$ = -0.078, CI = [-0.141, -0.015], $p_{(bonf)} = 0.0152$). The findings are illustrated in Fig. 3.

Similarly, the results of the GLMM showed that accuracy for the incongruent task was significantly lower than for the congruent task ($\beta$ = -0.40, CI=[-0.67, -0.13], $p = 0.004$) and a significant congruency × stimulation interaction ($\beta$ = -0.78, CI = [-1.1628, -0.4008], $p < 0.001$). After post-hoc tests and corrections, the results indicated that tDCS significantly increased accuracy for the incongruent task only ($\beta = 0.519$, CI= [0.094, 0.938], $p_{(bonf)} = 0.017$). The findings are illustrated in Fig. 3.

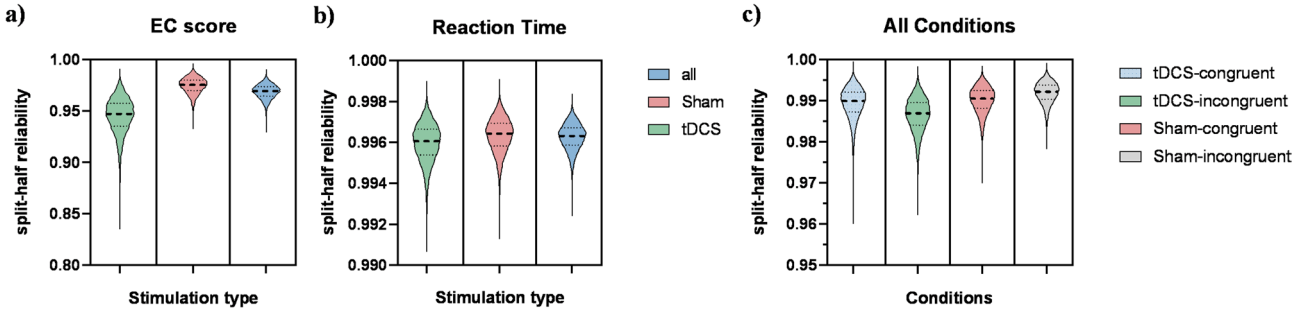



**Fig. 4**. High Reliability of the Test include: a) The split-half reliability calculated from the EC scores (incongruent RT-congruent RT) of the tDCS group and the sham group; b) The split-half reliability calculated from the RT of the tDCS group and the sham group. c) Split-half reliability under all conditions.

## High reliability of the test

After performing a permutation test, the EC score (incongruent RT - congruent RT) demonstrated an average split-half reliability of $r = 0.969$. The tDCS group exhibited an average split-half reliability of 0.945, while the sham group presented an average split-half reliability of 0.971. Regarding the RT, the average split-half reliability of the test was $r = 0.996$. Both the tDCS group and the sham group showed identical average split-half reliability scores of 0.996. All conditions exhibited split-half reliability coefficients exceeding 0.8, indicating high test reliability. Refer to Fig. 4 for detailed results.

## Side effects of electrical stimulation

The only adverse effect observed was a pricking sensation across the two stimulation conditions (mean score > 2). There was no statistically significant difference in side effects between-group comparisons (stimulation-task type). The findings are illustrated in Supplementary Table 2.

# Discussion

This study aims to investigate the distinct mechanisms of tDCS on baseline and conflict processing. HD-tDCS was utilized for precise intervention, in conjunction with a reliable EC test employing a steady-state block design within a Flanker task. This design enables the independent evaluation of baseline and conflict processing mechanisms. The findings indicate that tDCS reduced RT variability in both baseline and conflict processing, suggesting a general improvement on behavioral stability. After excluding the influence of the baseline, clear evidence shows that tDCS improves the efficiency of EC. To the best of our knowledge, this study is the first to differentiate between baseline and conflict processing in EC, further clarifying the mechanisms by which tDCS affects EC.

## HD-tDCS promotes behavioral stability

Our study demonstrates that HD-tDCS effectively reduces RT variability in baseline and conflict processing, contrasting with prior research on DLPFC interventions for enhancing EC[55]. Breitling et al. (2016) demonstrated that anodal tDCS on the right inferior frontal gyrus can decrease variability in individuals with ADHD during conflict processing[55]. Similarly, Qiao et al. (2022) found that 0.05 Hz oscillatory tDCS (O-tDCS) on the left DLPFC improved the stability of sustained attention[49]. These results collectively suggest that tDCS may enhance the stability of cognitive functions in general, possibly by optimizing attentional resource allocation, therefore allowing participants to focus more effectively on task-relevant stimuli[19,49]. Pre-task tDCS also positively impacts both superficial and deep PFC structures, facilitating network activity during subsequent cognitive tasks. This enhanced connectivity for cognitive demands, coupled with reduced default mode network activity, may aid in reconfiguring functional brain networks to meet cognitive challenges effectively[56].

Our study demonstrates that tDCS can influence baseline performance, which is essential for accurately evaluating intervention effects. Previous research has shown that tDCS can decrease RTs under baseline conditions, suggesting its ability to modify baseline states[21,34]. The findings of our study may be attributed to the use of a steady-state design, which entrains attention and perception by presenting stimuli at a constant frequency, resulting in improved performance and greater consistency in behavioral responses[57]. Given that tDCS can modify baseline states, ignoring changes in baseline states could introduce confounding intervention outcomes[20,23,25,26].

## HD-tDCS enhances the efficiency of conflict processing

In this study, HD-tDCS targeting the left DLPFC significantly enhanced the efficiency of conflict processing, showing a substantial effect. Our findings align with previous research that underscores the critical role of the left DLPFC in EC[17,18,21,58–60]. For instance, Dubreuil-Vall et al. investigated the effects of tDCS on both the left and right DLPFC in healthy individuals and patients with ADHD, revealing that stimulating the left DLPFC significantly reduced RTs in inconsistent trials, while right DLPFC stimulation and sham produced no significant impact[17,18]. Using HD-tDCS targeted at the left DLPFC, some studies effectively modulated cognitions in a region-specific manner[31,61]. Within the tDCS group, we observed a significant decrease in both RTs and error

rates, indicating enhanced EC. These results provide robust and precise evidence for the pivotal role of the left DLPFC in facilitating EC.

It is important to recognize that intervention outcomes are not only affected by stimulation parameters, but also by subjective factors. Participants' expectations can greatly impact intervention results, as positive expectations can lead to placebo effects even in the control group[62]. Despite this, our study showed distinct effects of stimulation, confirming its effectiveness. Active stimulation can cause temporary sensations like itching and tingling, while sham stimulation only delivers current at the beginning and end of sessions. This difference may lead participants to believe in the authenticity of the active condition, potentially enhancing positive effects[63,64]. Our study used a single-blind design and a somatization questionnaire. Results showed no significant difference in somatic sensations between the tDCS group and the sham group. This suggests that participants in both groups may have had similar expectations, potentially reducing between-group differences. However, it is also possible that each participants had varying expectations, leading to larger between-participant differences that could have masked between-group differences. In either case, this could result in the measured between-group differences being smaller than the actual differences. Therefore, the true effect of tDCS in this study may be greater.

### Steady-state block design improves the reliability of EC tests

The study utilized the steady-state block design and demonstrated its efficacy in enhancing the reliability of EC tests. This finding is consistent with our prior research ($r = 0.916$; $r = 0.906$) involving healthy adults[43,44]. In contrast, MacLeod et al. (2010) summarized 15 studies and reported an average split-half reliability for EC of 0.66[43], while more recent studies have also reported split-half reliabilities below 0.8[39,41]. The improved reliability of the steady-state block design may be attributed to the brain's sensitivity to task protocols.

Participants in event-related designs adjust their preparation, response strategy, and psychological state based on previous trials, even when conditions are fully randomized. This unpredictability can lead to inconsistent expectations and less stable psychological states, potentially confounding the true effects of conflict resolution. In contrast, the block design presents a stimuli at a fixed frequency, creating a stable and predictable environment for the brain, that reduces expectation fluctuations between trials, enhancing task reliability[44,57,66]. Block designs, as opposed to event-related designs (e.g., with randomized conditions), offer greater result stability due to their higher statistical power and improved signal-to-noise ratio, and have become an important experimental design method alongside event-related designs[67,68]. Moreover, the block design effectively segregates baseline and conflict processing, ensuring consistency in trial types within each block and minimizing the influence of CSE.

## Conclusion

The study elucidates two different mechanisms by which HD-tDCS enhances EC. Initially, tDCS exerts a general enhancement in behavioral stability, a factor often overlooked in previous studies, warranting consideration in future intervention research. Moreover, tDCS improves the efficiency of conflict resolution, providing clear evidence for the causal role of the left DLPFC in EC. The steady-state block paradigm ensures the high reliability of this study, emphasizing the crucial role of cognitive measurement methods in intervention research.

### Limitations of the study

Several limitations should be noted. First, two distinct mechanisms of HD-tDCS on EC were uncovered by behavioral data. The lack of neural function markers hinders a thorough interpretation of the underlying processes. Additionally, this study solely measured online behavioral performance during stimulation, without assessing performance before and after stimulation. Future research should compare task performance during both online and offline stimulation phases to investigate the temporal effects of tDCS on EC. Furthermore, the study lacked expectations collection, making it difficult to rule out the influence of subjective expectations. Future research should simultaneously consider both factors to provide a more comprehensive understanding.

## Data availability

The data that support the findings of this study are available from the corresponding author on request.

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## Author contributions

R.H.L.was responsible for data acquisition, analysis, and interpretation and wrote the main manuscript text; Q.L, and X.J.J. revised it substantively. Q.H., M.W and H.Y performed the experiment; Y.F.W. contributed substantively to this concept and revised it substantively. All authors reviewed the manuscript.

## Competing interests

The authors declare no competing interests.

## Additional information

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**Correspondence** and requests for materials should be addressed to Y.W.

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