Effects of Transcranial Direct Current Stimulation on Response Inhibition in Healthy Populations

Authors: Guo Zhihua, Lu Hongliang, Huang Peng, Zhu Xia, Zhu Xia

Date: 2022-03-15T15:34:52+00:00

Abstract

Response inhibition refers to the ability to suppress inappropriate or currently unnecessary behaviors. Studies have demonstrated that response inhibition is primarily associated with the functional integrity of the inferior frontal gyrus, dorsolateral prefrontal cortex, and pre-supplementary motor area. Transcranial direct current stimulation (tDCS) is a non-invasive brain stimulation technique. In recent years, research employing tDCS to modulate response inhibition by stimulating relevant brain regions in healthy populations has proliferated; however, the primary findings remain inconsistent. Elucidating the specific neural mechanisms through which tDCS influences response inhibition, reducing heterogeneity across tDCS studies, exploring more effective tDCS stimulation protocols, and establishing age-dependent differences in tDCS efficacy have become pressing issues requiring immediate resolution.

Full Text

Effects of Transcranial Direct Current Stimulation on Response Inhibition in Healthy Populations

Guo Zhihua, Lu Hongliang, Huang Peng, Zhu Xia
Department of Military Medical Psychology, Air Force Medical University, Xi'an 710032

Abstract: Response inhibition refers to the ability to suppress inappropriate or no-longer-needed behaviors. Research indicates that response inhibition is primarily associated with the functions of the inferior frontal gyrus, dorsolateral prefrontal cortex, and pre-supplementary motor area. Transcranial direct current stimulation (tDCS) is a non-invasive brain stimulation technique that

has gained increasing attention in recent years for its potential to modulate response inhibition by targeting these brain regions in healthy populations. However, the main findings remain inconsistent. Elucidating the specific neural mechanisms through which tDCS influences response inhibition, reducing heterogeneity across tDCS studies, exploring more effective stimulation protocols, and determining age-dependent differences in tDCS effects have become urgent priorities.

Keywords: response inhibition, transcranial direct current stimulation, inferior frontal gyrus, dorsolateral prefrontal cortex, pre-supplementary motor area, stop-signal task, go/nogo task

1 Introduction

When a response is required, we initiate action; yet when that response becomes inappropriate or unnecessary, we must be able to suppress the impulse. Consider crossing an intersection when the light suddenly turns red, forcing us to inhibit the forward motion; or a driver suppressing the ongoing action of pressing the accelerator upon seeing a reckless pedestrian; or halting an email transmission upon realizing it is addressed to the wrong recipient. All these situations involve response inhibition—the capacity to suppress inappropriate or no-longer-needed behaviors to enable flexible, goal-directed responses to environmental changes. As a critical component of executive function, response inhibition represents one of the most essential cognitive abilities for healthy populations and is closely linked to numerous pathological conditions. Deficits in response inhibition have been documented in attention deficit hyperactivity disorder (ADHD), obsessive-compulsive disorder (OCD), schizophrenia, and substance addiction. Furthermore, response inhibition is associated with decision-making and working memory, constituting a fundamental ability for normal daily functioning.

Response inhibition also manifests in specific capacities that can be enhanced to improve related abilities. For instance, military personnel' s response inhibition is relevant to combat effectiveness, with research demonstrating that improved response inhibition reduces shooting errors and significantly decreases civilian casualties in simulated combat scenarios. In recent years, investigating the neural mechanisms of response inhibition has attracted widespread research interest. The Go/Nogo task (GNG) and stop-signal task (SST) are common paradigms for studying response inhibition. Combined with neuroimaging, transcranial magnetic stimulation (TMS), and electroencephalography (EEG), extensive research has shown that response inhibition function is closely related to the prefrontal cortex (PFC) and basal ganglia, particularly the right inferior frontal gyrus (rIFG/rIFC), dorsolateral prefrontal cortex (DLPFC), and pre-supplementary motor area (pre-SMA).

The right inferior frontal gyrus is a crucial brain region for response inhibition. Studies of brain lesions and functional impairments provide strong support for rIFG' s role in response inhibition. Research has shown that patients with

rIFG damage exhibit impaired performance on response inhibition tasks, and TMS-induced disruption of rIFG function similarly reduces response inhibition capacity. The dorsolateral prefrontal cortex also contributes to response inhibition, with high-frequency rTMS over the left DLPFC improving performance on continuous performance tests. Numerous studies have additionally implicated the pre-SMA in response inhibition processes, with fMRI revealing increased pre-SMA activation during successful inhibition and pre-SMA damage leading to impaired SST performance. The basal ganglia, a collection of subcortical nuclei including the caudate, putamen, globus pallidus, and subthalamic nucleus, represent an essential component of response inhibition neural circuits. Diffusion-weighted imaging has demonstrated white matter tract connections between the IFC, subthalamic nucleus, and pre-SMA. Researchers have proposed a frontal-basal ganglia model to explain the neural mechanisms of response inhibition, wherein rIFG and pre-SMA generate stop commands transmitted to the basal ganglia, which then reduce motor cortex drive through output nuclei to suppress motor impulses.

Non-invasive brain stimulation techniques such as TMS have been widely used in response inhibition research. In recent years, transcranial direct current stimulation (tDCS) has emerged as a novel non-invasive technique garnering increasing attention. Unlike neuroimaging and EEG, which primarily reveal correlational relationships, tDCS enables investigation of causal relationships between brain function and behavior. tDCS differs from TMS in several respects. Mechanistically, TMS uses a magnetic coil to induce electric currents in underlying brain tissue, whereas tDCS delivers weak direct current (typically 0.5–2 mA) through scalp electrodes, partially penetrating the skull to affect cortical activity. tDCS has two polarities: anodal stimulation generally increases cortical excitability, while cathodal stimulation decreases it. Regarding safety, both techniques are generally safe when applied within recommended parameters, though rTMS carries a minimal risk of serious adverse events such as seizures, whereas tDCS typically produces only mild sensory effects without reports of severe adverse events. tDCS is thought to exert its effects through non-synaptic mechanisms (altering resting membrane potential) and synaptic-level long-term potentiation/depression mechanisms, with longer or repeated stimulation producing lasting after-effects and plasticity changes. Overall, tDCS represents a safe, tolerable, non-invasive, portable, and convenient technique for modulating cortical function and cognitive abilities.

Fortunately, response inhibition is plastic and can be enhanced through cognitive augmentation techniques. Two main approaches exist for healthy populations: cognitive training, which is time-consuming and relatively inefficient, and non-invasive brain stimulation, particularly tDCS, which offers technical advantages. An increasing number of researchers are exploring whether tDCS targeting specific anatomical regions can enhance response inhibition in healthy populations—a question with significant implications for increasing resilience to psychiatric disorders and improving related abilities. This review examines studies investigating tDCS effects on response inhibition in healthy participants,

focusing primarily on rIFG, DLPFC, and pre-SMA stimulation, with behavioral outcomes measured through GNG and SST performance. Nogo error rates (or accuracy) serve as the primary GNG metric, while stop-signal reaction time (SSRT) is the main SST indicator. We first discuss findings from each stimulation target, summarizing parameters and positive or negative results to enhance understanding of previous research, then address limitations in existing studies, and finally explore future directions for more scientifically rigorous, efficient, targeted, and standardized tDCS protocols for enhancing response inhibition.

2 Effects of tDCS Over the Right Inferior Frontal Gyrus on Response Inhibition

The right inferior frontal gyrus represents a higher-order brain region for response inhibition. Aron et al. (2014) described the rIFC and its associated neural network (the frontal-basal ganglia network) as a "brake" upon which response inhibition depends. Numerous tDCS studies have targeted rIFG to investigate its impact on response inhibition function (Table 1).

Anodal tDCS over rIFG can enhance response inhibition capacity. Jacobson et al. (2011) applied tDCS to participants' rIFG during SST performance, finding that anodal stimulation significantly reduced SSRT compared to sham stimulation, with no effect on a control task differing only by the absence of stop signals. This demonstrates region-specific modulation of response inhibition rather than general cognitive ability. Campanella et al. (2018) used conditional accuracy functions (CAF) to assess GNG performance, revealing that anodal rIFG stimulation reduced the accuracy decline typically observed with rapid responses, indicating improved inhibition efficiency. Additional studies have similarly demonstrated enhanced response inhibition following anodal tDCS over rIFG.

Neuroimaging research indicates that tDCS affects response inhibition at both behavioral and neurophysiological levels. Sandrini et al. (2020) conducted two experimental sessions, first establishing baseline SST performance, then administering anodal or sham tDCS over rIFC following resting-state fMRI. Post-stimulation fMRI and event-related fMRI during SST revealed that anodal tDCS significantly shortened SSRT, enhanced connectivity between pre-SMA and subthalamic nucleus during stop trials, and altered intrinsic connectivity among rIFC, caudate, pre-SMA, and right DLPFC.

Combining anodal tDCS with response inhibition training may produce superior enhancement effects. Ditye et al. (2012) investigated SST training combined with anodal tDCS over rIFG, administering 8 minutes of training and 15 minutes of tDCS (1.5 mA) daily for four days. Results showed that while training alone improved response inhibition, the combination with tDCS produced greater enhancement. Hogeveen et al. (2016) compared conventional tDCS, high-definition tDCS (HD-tDCS), and sham stimulation over rIFC during SST training versus control task training. Both active stimulation groups showed

improved response inhibition when combined with SST training but not with control training, suggesting that task relevance influences stimulation effects, possibly because tasks more closely related to response inhibition pre-activate corresponding neural populations, making them more susceptible to external current modulation.

Interestingly, researchers have distinguished between reactive and proactive inhibition, proposing that rIFG participates in both processes. Proactive inhibition is indexed by increased go-trial reaction times, while reactive inhibition is measured by SSRT reduction. Cunillera et al. (2014) applied tDCS to rIFC using a combined GNG-SST task, finding that anodal stimulation increased go-trial reaction times while decreasing SSRT, demonstrating dual effects on both inhibition types. However, Cunillera et al. (2016) failed to replicate these findings, observing increased go-trial reaction times but no significant SSRT changes. Another study targeting rIFG with SST found SSRT reduction during and after anodal stimulation without significant differences in go-trial reaction times. Given the limited research and inconsistent results, whether rIFG possesses dual inhibitory functions requires further investigation.

Although most studies demonstrate improved response inhibition following anodal rIFG stimulation, some report null effects, likely due to heterogeneity in stimulation parameters (current intensity, location, reference electrode position, polarity, duration), response inhibition measures, and population characteristics. For example, one recent study using dual-tDCS over rIFG and right DLPFC with 9 cm^2 electrodes found no behavioral changes, possibly because proximal stimulation sites and large electrode areas caused current dispersion. Methodological differences, such as using the relatively simple GNG task versus the adaptively difficult SST, may produce ceiling effects. Campanella et al. (2018) suggested that overall error rates lack sensitivity for detecting subtle GNG performance changes, which may explain negative findings in Campanella et al. (2017). Fujiyama et al. (2021) demonstrated age-dependent tDCS effects, with anodal rIFG stimulation reducing SSRT in young adults (24 $\pm$ 4.9 years) but not older adults (69 $\pm$ 5.8 years). These findings underscore the need to consider multiple factors to reduce experimental heterogeneity.

Table 1 Effects of tDCS on response inhibition function in the right inferior frontal gyrus region

Study	Task	Stimulation	Current Intensity	Duration	Main Effects
Jacobson et al. (2011)	SST	A/C/S	1 mA	10 min	Anodal stimulation reduced SSRT; cathodal had no significant effect

Study	Task	Stimulation	Current Intensity	Duration	Main Effects
Ditye et al. (2012)	SST	A/S	1.5 mA	15 min	Training reduced SSRT; anodal stimulation enhanced training effects
Cunillera et al. (2014)	GNG-SST	A/S	1 mA	18 min	Anodal stimulation reduced SSRT and increased GoRT
Dambacher et al. (2015)	GNG	A/C/S	1 mA	21.75 min	No significant differences in Nogo error rates across groups
Stramaccia et al. (2015)	SST	A/C/S	1 mA	20 min	Anodal stimulation reduced SSRT; cathodal had no significant effect
Cai et al. (2016)	SST	A/S	1 mA	15 min	Anodal stimulation reduced SSRT and increased GoRT
Cunillera et al. (2016)	GNG-SST	A/S	1 mA	20 min	Anodal stimulation had no significant effect on SSRT but increased GoRT

Study	Task	Stimulation	Current Intensity	Duration	Main Effects
Hogeveen et al. (2016)	SST	A	1.5 mA	20 min	HD-tDCS combined with SST training reduced SSRT; HD-tDCS with CRT training had no effect
Castro-Meneses et al. (2016)	SST	A/S	1 mA	15 min	Anodal stimulation reduced SSRT; GoRT showed no significant difference
Campanella et al. (2017)	GNG	A/S	1.5 mA	20 min	No significant difference in Nogo error rates between anodal and sham
Campanella et al. (2018)	GNG	A/S	1.5 mA	20 min	Anodal stimulation reduced accuracy decline during rapid responses
Leite et al. (2018)	GNG	A/S	2 mA	30 min	No significant difference in Nogo accuracy between anodal and sham

Study	Task	Stimulation	Current Intensity	Duration	Main Effects
Li et al. (2019)	SST	A/C/S	1.5 mA	4 min 12 sec	Anodal stimulation reduced SSRT; cathodal had no significant effect
Chen et al. (2019)	modified SST	A	1.5 mA	20 min	Anodal stimulation reduced SSRT
Sandrini et al. (2020)	SST	A/S	1.5 mA	20 min	Anodal stimulation shortened SSRT
Thunberg et al. (2020)	SST	A/S	1.5 mA	20 min	No significant difference in SSRT between anodal and sham
Friehs, Brauner et al. (2021)	SST	A/C/S	1.5 mA	20 min	No significant differences in SSRT across groups
Fujiyama et al. (2021)	modified SST	A/S	1.5 mA	20 min	Anodal stimulation significantly reduced SSRT in young adults but not older adults

Note: A: anodal stimulation; C: cathodal stimulation; S: sham stimulation; GNG: go/nogo task; GoRT: go-trial reaction time; SST: stop-signal task; modified SST: SST variant; SSRT: stop-signal reaction time; GNG-SST: combined GNG and SST task

3 Effects of tDCS Over the Dorsolateral Prefrontal Cortex on Response Inhibition

The dorsolateral prefrontal cortex is associated with numerous cognitive functions including working memory, attention, decision-making, and cognitive control, but it also represents an important region for response inhibition. In recent years, DLPFC has become a key target for tDCS studies of response inhibition function (Table 2).

Research demonstrates that tDCS over DLPFC can modulate response inhibition, with studies targeting both left and right hemispheres. Friehs and Frings (2018) targeted right DLPFC, finding that anodal stimulation reduced SSRT compared to sham. A subsequent study using an SST variant replicated this effect. In another experiment, cathodal stimulation over right DLPFC increased SSRT, indicating impaired response inhibition. Together, these findings suggest polarity-specific modulation: anodal stimulation enhances while cathodal stimulation impairs response inhibition. Nejati et al. (2018) applied anodal stimulation to left DLPFC, observing increased Nogo accuracy compared to sham, while other left DLPFC studies also reported SSRT reductions. These results indicate that both right and left DLPFC are involved in response inhibition, though the functional lateralization remains to be fully elucidated.

Combining tDCS with response inhibition training has yielded mixed results. Dousset et al. (2021) employed four days of tDCS combined with GNG training, finding that anodal right DLPFC stimulation produced the greatest improvement in Nogo accuracy at one-week follow-up. However, Sedgmond et al. (2019) found no significant effects of single-session tDCS combined with GNG training, possibly due to individual variability and unstable single-session effects, suggesting the need for more intensive investigation of combined protocols.

Despite evidence for tDCS effects on response inhibition, several studies report null behavioral outcomes. Lapenta et al. (2014) found no behavioral differences between anodal right DLPFC stimulation and sham on a modified GNG task, though EEG revealed reduced N2 amplitude and increased P3a amplitude, suggesting enhanced inhibition at the neurophysiological level. Stramaccia et al. (2015) observed no SSRT changes following right DLPFC stimulation, while anodal rIFG stimulation significantly reduced SSRT, possibly reflecting shorter-lasting DLPFC effects or differential contributions of distinct brain regions. Chen et al. (2021) reported that both anodal and cathodal stimulation over right DLPFC reduced SSRT, contrasting with Friehs and Frings (2019) who found cathodal stimulation increased SSRT. These discrepancies may stem from differences in reference electrode placement and resulting indirect modulatory effects on adjacent frontal regions.

Individual differences substantially influence tDCS effects on response inhibition. Nieratschker et al. (2015) found that cathodal tDCS over left DLPFC impaired response inhibition only in COMT Val homozygotes, not Met allele carriers, suggesting genetic modulation via prefrontal dopaminergic activity. However,

Plewnia et al. (2013) found no COMT genotype interaction, indicating the need for further investigation. Weidacker et al. (2016) demonstrated that higher cold-heartedness scores predicted better performance under cathodal stimulation, potentially reflecting restoration of excitatory-inhibitory balance. Wu et al. (2021) showed that baseline performance level moderated tDCS effects, with cathodal stimulation improving Nogo accuracy in low-baseline participants while impairing high-baseline performers, resulting in null group-level effects. These findings highlight the importance of considering individual variability in experimental design, analysis, and application to reduce heterogeneity and advance personalized neuromodulation approaches.

Table 2 Effects of tDCS on response inhibition function in the dorsolateral prefrontal cortex

Study	Stimulation	Target	Current Intensity	Duration	Main Effects
Plewnia et al. (2013)	A/C/S	left DLPFC	2 mA	20 min	No COMT genotype difference in tDCS effects on Nogo accuracy
Lapenta et al. (2014)	A	right DLPFC	2 mA	30 min	No behavioral difference between anodal and sham; EEG showed neurophysiological changes
Nieratschker et al. (2015)	C	left DLPFC	2 mA	20 min	Cathodal stimulation reduced Nogo accuracy only in COMT Val homozygotes
Stramaccia et al. (2015)	A/C/S	right DLPFC	1 mA	20 min	No significant SSRT differences from sham

Study	Stimulation	Target	Current Intensity	Duration	Main Effects
Weidacker et al. (2016)	A/C/S	right DLPFC	1 mA	20 min	Higher cold-heartedness scores predicted better performance under cathodal stimulation
Mansouri et al. (2017)	A	left DLPFC	1.5 mA	20 min	Anodal stimulation reduced SSRT under fast-paced music
Nejati et al. (2018)	A/C/S	left DLPFC	1.5 mA	20 min	Anodal stimulation increased Nogo accuracy
Wang et al. (2018)	A	right DLPFC	1.5 mA	20 min	Anodal stimulation reduced SSRT
Friehs & Frings (2018)	A	right DLPFC	1.5 mA	20 min	Anodal stimulation reduced SSRT
Fehring et al. (2019)	A	left DLPFC	1.5 mA	20 min	Anodal stimulation reduced SSRT
Friehs & Frings (2019)	C	right DLPFC	1.5 mA	20 min	Cathodal stimulation increased SSRT
Sedgmond et al. (2019)	A	right DLPFC	1.5 mA	20 min	No difference in Nogo accuracy between anodal and sham with training

Study	Stimulation	Target	Current Intensity	Duration	Main Effects
Chen et al. (2021)	A/C/S	right DLPFC	1.5 mA	20 min	Both anodal and cathodal stimulation reduced SSRT compared to sham
Dousset et al. (2021)	A	right DLPFC	1.5 mA	20 min	Anodal stimulation with training reduced GoRT and Nogo error rates
Friehs, Brauner et al. (2021)	A/C/S	right DLPFC	1.5 mA	20 min	No significant SSRT differences across groups
Friehs, Dechant et al. (2021)	A	right DLPFC	1.5 mA	20 min	Anodal stimulation reduced SSRT
Wu et al. (2021)	A/C/S	right DLPFC	1.5 mA	20 min	No group-level differences in Nogo accuracy or SSRT

Note: A: anodal stimulation; C: cathodal stimulation; S: sham stimulation; DLPFC: dorsolateral prefrontal cortex; GNG: go/nogo task; PGNG: parametric go/nogo task; modified GNG: GNG variant; SST: stop-signal task; modified SST: SST variant; GoRT: go-trial reaction time; SSRT: stop-signal reaction time

4 Effects of tDCS Over the Pre-supplementary Motor Area on Response Inhibition

The pre-supplementary motor area is a critical neural substrate for response inhibition and an important node in the frontal-basal ganglia model, making it

a popular target for tDCS research (Table 3).

Extensive behavioral evidence demonstrates that anodal tDCS over pre-SMA enhances response inhibition. Hsu et al. (2011) applied anodal, cathodal, and sham stimulation to pre-SMA during SST performance. Compared to other conditions, anodal stimulation significantly reduced stop-trial error rates, though SSRT did not differ significantly. This may reflect the use of a fixed SSD determined from pre-testing without accounting for tDCS-induced changes. Kwon and Kwon (2013a, 2013b) replicated these findings, showing that anodal pre-SMA stimulation reduced SSRT compared to sham, with effects persisting during and after stimulation. Fujiyama et al. (2021) demonstrated that anodal pre-SMA stimulation significantly reduced SSRT in older adults (68.5 $\pm$ 5.3 years), confirming pre-SMA as an important target for modulating response inhibition.

Anodal tDCS over pre-SMA shows neurophysiological as well as behavioral effects. Liang et al. (2014) replicated Hsu et al.' s findings while additionally demonstrating SSRT reduction. Multiscale entropy analysis of EEG signals revealed that higher entropy correlated with better inhibition performance and that anodal tDCS further increased entropy. Yu et al. (2015) similarly found SSRT reduction following anodal pre-SMA stimulation, accompanied by increased blood oxygen level-dependent (BOLD) responses in pre-SMA and ventromedial prefrontal cortex (vmPFC). The tDCS-induced BOLD signal increase correlated positively with improved inhibition efficiency and enhanced pre-SMA-vmPFC functional connectivity.

Despite most studies demonstrating enhanced response inhibition following anodal pre-SMA stimulation, some report no behavioral improvement. Bender et al. (2017) found no differences in SSRT or inhibition success rates between anodal stimulation and control conditions, possibly due to lower current intensity and shorter duration compared to previous studies, or different reference electrode placement (right mastoid versus left cheek). Fujiyama et al. (2021) showed age-dependent effects, with anodal stimulation reducing SSRT in older but not younger adults (22.4 $\pm$ 4.2 years), potentially reflecting anatomical features affecting stimulation efficacy or true age-dependent effects. As reported in the literature, variations in current intensity, duration, reference electrode position, and population characteristics can produce different outcomes.

Table 3 Effects of tDCS on response inhibition function in the pre-supplementary motor area

Study	Task	Stimulation	Current Intensity	Duration	Main Effects
Hsu et al. (2011)	SST	A/C/S	1.5 mA	10 min	Anodal stimulation reduced stop-trial error rates; no SSRT differences
Kwon & Kwon (2013a)	SST	A	1 mA	10 min	Anodal stimulation reduced SSRT
Kwon & Kwon (2013b)	SST	A	1 mA	10 min	Anodal stimulation reduced SSRT during and after stimulation
Liang et al. (2014)	SST	A	1.5 mA	10 min	Anodal stimulation reduced both stop-trial error rates and SSRT
Yu et al. (2015)	SST	A	1.5 mA	20 min	Anodal stimulation reduced SSRT
Bender et al. (2017)	modified SST	A/C/S	0.7 mA	9 min	No significant SSRT differences from sham
Fujiyama et al. (2021)	modified SST	A/S	1.5 mA	20 min	Anodal stimulation reduced SSRT in older adults but not young adults

Note: A: anodal stimulation; C: cathodal stimulation; S: sham stimulation; SST: stop-signal task; modified SST: SST variant; SSRT: stop-signal reaction time

5 Summary and Outlook

Numerous studies have examined tDCS effects on response inhibition by targeting different brain regions, yielding meaningful results that demonstrate tDCS' s potential as a tool for enhancing response inhibition in healthy populations. However, several limitations and unresolved issues remain.

First, the neural mechanisms underlying tDCS modulation of response inhibition are not fully understood. Two key questions persist: the precise physiological neural circuits of response inhibition, particularly the temporal dynamics of cortical region involvement, and the identification of critical brain regions whose stimulation produces maximal effects. While the frontal-basal ganglia model provides a framework incorporating rIFG, DLPFC, pre-SMA, and basal ganglia, it has notable gaps. The temporal sequence of cortical region activation remains unclear, with inconsistent reports about whether rIFG functions upstream or downstream of pre-SMA, or whether bidirectional connections exist. Methodologies such as electrocorticography may help clarify these temporal dynamics. Additionally, the current model does not adequately incorporate DLPFC, despite evidence for its involvement, suggesting more complex neural circuits remain to be elucidated. Furthermore, it is uncertain which brain region constitutes the critical target for tDCS modulation of response inhibition. While stimulation of rIFG, DLPFC, and pre-SMA all affect response inhibition, these conclusions derive from different experimental designs and parameters, preventing direct comparison. Future studies should employ rigorous controlled designs to compare different stimulation targets within the same experiment, combining behavioral, neurophysiological, and neuroimaging techniques to isolate the specific contributions of each region.

Second, research findings exhibit substantial heterogeneity. While most studies demonstrate tDCS can modulate response inhibition, null results also emerge due to individual differences, stimulation parameters (current magnitude, duration, electrode size, position), and behavioral task characteristics (analysis methods, difficulty). Notably, different analytical approaches to the same data can yield inconsistent results. Campanella et al. (2017) found no group differences using traditional error rate analysis, yet Campanella et al. (2018) detected improved performance using conditional accuracy functions on the same dataset. Similarly, drift diffusion model reanalysis of existing data revealed that anodal stimulation increased inhibition tendency while reducing impulsivity. Future research must carefully control for these factors to reduce heterogeneity and improve reproducibility. We recommend: (1) Controlling individual differences through homogeneous sampling and within-subject designs, while addressing potential blinding issues through realistic sham protocols and post-stimulation questionnaires; (2) Using standardized tDCS parameters, with electrode placement guided by the 10-20 system or fMRI, current intensities of 0.5–2 mA, durations of 20 minutes, and computational modeling to verify electric field distribution; and (3) Optimizing behavioral tasks to prevent ceiling/floor effects, using adaptive difficulty adjustment, standardized protocols, and consensus guidelines

for task implementation and analysis.

Third, tDCS research requires improved spatial resolution. Most studies use conventional tDCS with large rectangular electrodes (25–35 cm^2), resulting in low spatial resolution and diffuse current spread that complicates mechanistic interpretation. High-definition tDCS (HD-tDCS) using small circular electrodes in a 4$×$1 montage provides higher spatial resolution and more focal stimulation, producing more robust behavioral and neurophysiological effects. However, few studies of response inhibition in healthy populations have employed HD-tDCS. Future research should increasingly utilize HD-tDCS to enhance spatial precision, simplify mechanistic interpretations, and improve result reliability.

Fourth, the combination of tDCS with response inhibition training requires further investigation. While both training alone and tDCS alone can enhance response inhibition, combined approaches may be more effective. Studies have employed online (simultaneous) and offline (sequential) combination protocols with inconsistent results. Ditye et al. (2012) found offline combination superior to training alone, while Hogeveen et al. (2016) demonstrated online combination benefits. However, Sedgmond et al. (2019) found no effect of online combination, and protocols vary in stimulation frequency and timing. Future research must systematically investigate optimal combination approaches, including online versus offline protocols and stimulation parameters.

Fifth, different stimulation protocols warrant exploration. Most studies employ single-session stimulation with effects lasting approximately 90 minutes, though HD-tDCS effects may persist for 2 hours. Multi-session stimulation can produce longer-lasting effects and has been safely applied in other domains, yet few studies have examined repeated stimulation for response inhibition in healthy populations. Future research should investigate the efficacy and long-term effects of multi-session protocols. Additionally, combining tDCS with other stimulation methods, such as transcutaneous auricular vagus nerve stimulation (taVNS), may produce synergistic effects. Multi-site stimulation targeting multiple brain regions simultaneously represents another promising approach that has shown benefits in motor and working memory studies but remains unexplored for response inhibition.

Finally, research across different age groups is limited. Most studies recruit young adults (20–30 years), with minimal research in children and only one study in older adults. Fujiyama et al. (2021) demonstrated that while older adults showed preserved plasticity, tDCS effects were evident only for pre-SMA stimulation, not rIFG, suggesting age-dependent differences in stimulation efficacy. Given that response inhibition declines with age and develops throughout childhood, investigating tDCS effects across the lifespan is both theoretically important and clinically relevant. Future studies should include diverse age groups to understand developmental and aging-related differences and develop age-appropriate protocols.

In summary, tDCS is a safe and effective non-invasive brain stimulation tech-

nique that can modulate neural activity in brain regions involved in response inhibition to affect cognitive function. However, current research has limitations that must be addressed. Future studies should elucidate neural mechanisms, reduce heterogeneity, increase spatial resolution through HD-tDCS, optimize combination with training, explore multi-session and multi-site protocols, and investigate effects across different age groups. Such advances will provide stronger evidence for optimizing tDCS applications to enhance response inhibition in healthy populations.

References

Achala, H. R., Domenico, S. I., Ayaz, H., Gulrajani, S., Lam, J. & Ruocco, A. C. (2014). Differentiating functions of the lateral and medial prefrontal cortex in motor response inhibition. *Neuroimage*, 85 pt 1, 423–431.

Alderson, R., Patros, C., Tarle, S., Hudec, K., Kasper, L. & Lea, S. (2017). Working memory and behavioral inhibition in boys with ADHD: An experimental examination of competing models. *Child Neuropsychology*, 23(3), 255–272.

Alizadehgoradel, J., Nejati, V., Movahed, F. S., Imani, S., Taherifard, M., Mosayebi-Samani, M., ···Salehinejad, M. A. (2020). Repeated stimulation of the dorsolateral-prefrontal cortex improves executive dysfunctions and craving in drug addiction: A randomized, double-blind, parallel-group study. *Brain Stimulation*, 13(3), 582–594.

Aron, A. R. (2007). The neural basis of inhibition in cognitive control. *Neuroscientist*, 13(3), 214–228.

Aron, A. R., Behrens, T. E., Smith, S., Frank, M. J. & Poldrack, R. A. (2007). Triangulating a cognitive control network using diffusion-weighted magnetic resonance imaging (MRI) and functional MRI. *Journal of Neuroscience*, 27(14), 3743–3752.

Aron, A. R., Durston, S., Eagle, D. M., Logan, G. D., Stinear, C. M. & Stuphorn, V. (2007). Converging evidence for a fronto-basal-ganglia network for inhibitory control of action and cognition. *Journal of Neuroscience*, 27(44), 11860–11864.

Aron, A. R., Fletcher, P. C., Bullmore, E. T., Sahakian, B. J. & Robbins, T. W. (2003). Stop-signal inhibition disrupted by damage to right inferior frontal gyrus in humans. *Nature Neuroscience*, 6(2), 115–116.

Aron, A. R., Herz, D. M., Brown, P., Forstmann, B. U. & Zaghloul, K. (2016). Frontosubthalamic circuits for control of action and cognition. *Journal of neuroscience*, 36(45), 11489–11495.

Aron, A. R. & Poldrack, R. A. (2006). Cortical and subcortical contributions to stop signal response inhibition: Role of the subthalamic nucleus. *Journal of Neuroscience*, 26(9), 2424–2433.

Aron, A. R., Robbins, T. W. & Poldrack, R. A. (2014). Inhibition and the right inferior frontal cortex: One decade on. *Trends in Cognitive Sciences*, 18(4), 177–185.

Bender, A., Filmer, H. & Dux, P. (2017). Transcranial direct current stimulation of superior medial frontal cortex disrupts response selection during proactive response inhibition. *Neuroimage*, 158, 455–465.

Benikos, N., Johnstone, S. J. & Roodenrys, S. J. (2013). Short-term training in the Go/Nogo task: Behavioural and neural changes depend on task demands. *International Journal of Psychophysiology*, 87(3), 301–312.

Biggs, A. T., Cain, M. S. & Mitroff, S. R. (2015). Cognitive training can reduce civilian casualties in a simulated shooting environment. *Psychological Science*, 26(8), 1164–1176.

Bikson, M., Grossman, P., Thomas, C., Zannou, A., Jiang, J., Adnan, T., ··· Woods, A. (2016). Safety of transcranial direct current stimulation: Evidence based update 2016. *Brain Stimulation*, 9(5), 641–661.

Borgomaneri, S., Serio, G. & Battaglia, S. (2020). Please, don' t do it! Fifteen years of progress of non-invasive brain stimulation in action inhibition. *Cortex*, 132, 404–422.

Boroda, E., Krueger, A. M., Bansal, P., Schumacher, M. J., Roy, A. V., Boys, C. J., ···Wozniak, J. R. (2020). A randomized controlled trial of transcranial direct current stimulation and cognitive training in children with fetal alcohol spectrum disorder. *Brain Stimulation*, 13(4), 1059–1068.

Bortoletto, M., Rodella, C., Salvador, R., Miranda, P. C. & Miniussi, C. (2016). Reduced current spread by concentric electrodes in transcranial electrical stimulation (tES). *Brain Stimulation*, 9(4), 527–530.

Braga, M., Barbiani, D., Emadi Andani, M., Villa-Sanchez, B., Tinazzi, M. & Fiorio, M. (2021). The role of expectation and beliefs on the effects of non-invasive brain stimulation. *Brain Sciences*, 11(11), 1526.

Brunelin, J., Mondino, M., Bation, R., Palm, U., Saoud, M. & Poulet, E. (2018). Transcranial direct current stimulation for obsessive-compulsive disorder: A systematic review. *Brain Sciences*, 8(2), 37.

Cai, Y., Li, S. Y., Liu, J., Li, D. W., Feng, Z. F., Wang, Q., ···Xue, G. (2016). The role of the frontal and parietal cortex in proactive and reactive inhibitory control: A transcranial direct current stimulation study. *Journal of Cognitive Neuroscience*, 28(1), 177–186.

Campanella, S., Schroder, E., Monnart, A., Vanderhasselt, M., Duprat, R., Rabijns, M., ···Baeken, C. (2017). Transcranial direct current stimulation over the right frontal inferior cortex decreases neural activity needed to achieve inhibition: A double-blind ERP study in a male population. *Clinical EEG and Neuroscience*, 48(3), 163–171.

Campanella, S., Schroder, E., Vanderhasselt, M.-A., Baeken, C., Kornreich, C., Verbanck, P. & Burle, B. (2018). Short-term impact of tDCS over the right inferior frontal cortex on impulsive responses in a Go/No-go task. *Clinical EEG and Neuroscience*, 49(6), 398–406.

Castro-Meneses, L., Johnson, B. & Sowman, P. (2016). Vocal response inhibition is enhanced by anodal tDCS over the right prefrontal cortex. *Experimental Brain Research*, 234(1), 185–195.

Chamberlain, S., Blackwell, A., Fineberg, N., Robbins, T. & Sahakian, B. (2005). The neuropsychology of obsessive compulsive disorder: The importance of failures in cognitive and behavioural inhibition as candidate endophenotypic markers. *Neuroscience and Biobehavioral Reviews*, 29(3), 399–419.

Chambers, C., Bellgrove, M., Stokes, M., Henderson, T., Garavan, H., Robertson, I., ···Mattingley, J. (2006). Executive "brake failure" following deactivation of human frontal lobe. *Journal of Cognitive Neuroscience*, 18(3), 444–455.

Chan, M. M. Y., Yau, S. S. Y. & Han, Y. M. Y. (2021). The neurobiology of prefrontal transcranial direct current stimulation (tDCS) in promoting brain plasticity: A systematic review and meta-analyses of human and rodent studies. *Neuroscience and Biobehavioral Reviews*, 125, 392–416.

Chen, S., Jackson, T., Dong, D., Zhang, X. & Chen, H. (2019). Exploring effects of single-session anodal tDCS over the inferior frontal gyrus on responses to food cues and food cravings among highly disinhibited restrained eaters: A preliminary study. *Neuroscience Letters*, 706, 211–216.

Chen, T., Wang, H., Wang, X., Zhu, C., Zhang, L., Wang, K. & Yu, F. (2021). Transcranial direct current stimulation of the right dorsolateral prefrontal cortex improves response inhibition. *International Journal of Psychophysiology*, 162, 34–39.

Clark, L., Blackwell, A. D., Aron, A. R., Turner, D. C., Dowson, J., Robbins, T. W. & Sahakian, B. J. (2007). Association between response inhibition and working memory in adult ADHD: A link to right frontal cortex pathology? *Biological Psychiatry*, 61(12), 1395–1401.

Coffman, B. A., Clark, V. P. & Parasuraman, R. (2014). Battery powered thought: Enhancement of attention, learning, and memory in healthy adults using transcranial direct current stimulation. *Neuroimage*, 85, 895–908.

Coxon, J. P., Goble, D. J., Leunissen, I., Van Impe, A., Wenderoth, N. & Swinnen, S. P. (2016). Functional brain activation associated with inhibitory control deficits in older adults. *Cerebral Cortex*, 26(1), 12–22.

Cunillera, T., Brignani, D., Cucurell, D., Fuentemilla, L. & Miniussi, C. (2016). The right inferior frontal cortex in response inhibition: A tDCS-ERP co-registration study. *Neuroimage*, 140, 66–75.

Cunillera, T., Fuentemilla, L., Brignani, D., Cucurell, D. & Miniussi, C. (2014).

A simultaneous modulation of reactive and proactive inhibition processes by anodal tDCS on the right inferior frontal cortex. *PLoS One*, 9(11), e113537.

Dagan, M., Herman, T., Harrison, R., Zhou, J., Giladi, N., Ruffini, G., . . . Hausdorff, J. M. (2018). Multitarget transcranial direct current stimulation for freezing of gait in Parkinson' s disease. *Movement Disorders*, 33(4), 642–646.

Dambacher, F., Sack, A., Lobbestael, J., Arntz, A., Brugman, S. & Schuhmann, T. (2014). A network approach to response inhibition: Dissociating functional connectivity of neural components involved in action restraint and action cancellation. *The European Journal of Neuroscience*, 39(5), 821–831.

Dambacher, F., Schuhmann, T., Lobbestael, J., Arntz, A., Brugman, S. & Sack, A. (2015). No effects of bilateral tDCS over inferior frontal gyrus on response inhibition and aggression. *PLoS One*, 10(7), e0132170.

Datta, A., Bansal, V., Diaz, J., Patel, J., Reato, D. & Bikson, M. (2009). Gyri-precise head model of transcranial direct current stimulation: Improved spatial focality using a ring electrode versus conventional rectangular pad. *Brain Stimulation*, 2(4), 201–207.e1.

Davis, S. E. & Smith, G. A. (2019). Transcranial direct current stimulation use in warfighting: Benefits, risks, and future prospects. *Frontiers in Human Neuroscience*, 13, 114.

de Boer, N. S., Schluter, R. S., Daams, J. G., van der Werf, Y. D., Goudriaan, A. E. & van Holst, R. J. (2021). The effect of non-invasive brain stimulation on executive functioning in healthy controls: A systematic review and meta-analysis. *Neuroscience and Biobehavioral Reviews*, 125, 122–147.

de Wit, S., de Vries, F., van der Werf, Y., Cath, D., Heslenfeld, D., Veltman, E., ···van den Heuvel, O. (2012). Presupplementary motor area hyperactivity during response inhibition: A candidate endophenotype of obsessive-compulsive disorder. *American Journal of Psychiatry*, 169(10), 1100–1108.

Di Rosa, E., Brigadoi, S., Cutini, S., Tarantino, V., Dell' Acqua, R., Mapelli, D., ···Vallesi, A. (2019). Reward motivation and neurostimulation interact to improve working memory performance in healthy older adults: A simultaneous tDCS-fNIRS study. *Neuroimage*, 202, 116062.

Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, 64, 135–168.

Ditye, T., Jacobson, L., Walsh, V. & Lavidor, M. (2012). Modulating behavioral inhibition by tDCS combined with cognitive training. *Experimental Brain Research*, 219(3), 363–368.

Dousset, C., Ingels, A., Schroder, E., Angioletti, L., Balconi, M., Kornreich, C. & Campanella, S. (2021). Transcranial direct current stimulation combined with cognitive training induces response inhibition facilitation through distinct

neural responses according to the stimulation site: A follow-up event-related potentials study. *Clinical EEG and Neuroscience*, 52(3), 181–192.

Duann, J. R., Ide, J. S., Luo, X. & Li, C. S. (2009). Functional connectivity delineates distinct roles of the inferior frontal cortex and presupplementary motor area in stop signal inhibition. *Journal of Neuroscience*, 29(32), 10171–10177.

Dubreuil-Vall, L., Chau, P., Ruffini, G., Widge, A. S. & Camprodon, J. A. (2019). tDCS to the left DLPFC modulates cognitive and physiological correlates of executive function in a state-dependent manner. *Brain Stimulation*, 12(6), 1456–1463.

Dumel, G., Bourassa, M. E., Desjardins, M., Voarino, N., Charlebois-Plante, C., Doyon, J. & De Beaumont, L. (2016). Multisession anodal tDCS protocol improves motor system function in an aging population. *Neural Plasticity*, 2016, 5961362.

Erika-Florence, M., Leech, R. & Hampshire, A. (2014). A functional network perspective on response inhibition and attentional control. *Nature Communications*, 5, 4073.

Fehring, D. J., Illipparampil, R., Acevedo, N., Jaberzadeh, S., Fitzgerald, P. B. & Mansouri, F. A. (2019). Interaction of task-related learning and transcranial direct current stimulation of the prefrontal cortex in modulating executive functions. *Neuropsychologia*, 131, 148–159.

Filmer, H. L., Dux, P. E. & Mattingley, J. B. (2014). Applications of transcranial direct current stimulation for understanding brain function. *Trends in Neurosciences*, 37(12), 742–753.

Floden, D. & Stuss, S. (2006). Inhibitory control is slowed in patients with right superior medial frontal damage. *Journal of Cognitive Neuroscience*, 18(11), 1843–1849.

Friehs, M. A., Brauner, L. & Frings, C. (2021). Dual-tDCS over the right prefrontal cortex does not modulate stop-signal task performance. *Experimental Brain Research*, 239(3), 811–820.

Friehs, M. A., Dechant, M., Vedress, S., Frings, C. & Mandryk, R. L. (2021). Shocking advantage! Improving digital game performance using non-invasive brain stimulation. *International Journal of Human-Computer Studies*, 148, 102582.

Friehs, M. A. & Frings, C. (2018). Pimping inhibition: Anodal tDCS enhances stop-signal reaction time. *Journal of Experimental Psychology-Human Perception and Performance*, 44(12), 1933–1945.

Friehs, M. A. & Frings, C. (2019). Cathodal tDCS increases stop-signal reaction time. *Cognitive Affective & Behavioral Neuroscience*, 19(5), 1129–1142.

Friehs, M. A., Frings, C. & Hartwigsen, G. (2021). Effects of single-session transcranial direct current stimulation on reactive response inhibition. *Neuroscience*

and Biobehavioral Reviews, 128, 749–765.

Fritsch, B., Reis, J., Martinowich, K., Schambra, H. M., Ji, Y. Y., Cohen, L. G. & Lu, B. (2010). Direct current stimulation promotes BDNF-dependent synaptic plasticity: Potential implications for motor learning. *Neuron*, 66(2), 198–204.

Fujiyama, H., Tan, J., Puri, R. & Hinder, M. R. (2021). Influence of tDCS over right inferior frontal gyrus and pre-supplementary motor area on perceptual decision-making and response inhibition: A healthy ageing perspective. *Neurobiology of Aging*, 109, 11–21.

Gbadeyan, O., McMahon, K., Steinhauser, M. & Meinzer, M. (2016). Stimulation of dorsolateral prefrontal cortex enhances adaptive cognitive control: A high-definition transcranial direct current stimulation study. *Journal of Neuroscience*, 36(50), 12530–12536.

Gbadeyan, O., Steinhauser, M., McMahon, K. & Meinzer, M. (2016). Safety, tolerability, blinding efficacy and behavioural effects of a novel MRI-compatible, high-definition tDCS set-up. *Brain Stimulation*, 9(4), 547–556.

Gowda, S. M., Narayanaswamy, J. C., Hazari, N., Bose, A., Chhabra, H., Balachander, S., ···Reddy, Y. C. J. (2019). Efficacy of pre-supplementary motor area transcranial direct current stimulation for treatment resistant obsessive compulsive disorder: A randomized, double blinded, sham controlled trial. *Brain Stimulation*, 12(4), 922–929.

Guo, H., Zhang, Z., Da, S., Sheng, X. & Zhang, X. (2018). High-definition transcranial direct current stimulation (HD-tDCS) of left dorsolateral prefrontal cortex affects performance in balloon analogue risk task (BART). *Brain and Behavior*, 8(2), e00884.

Hannah, R. & Aron, A. R. (2021). Towards real-world generalizability of a circuit for action-stopping. *Nature Reviews Neuroscience*, 22(9), 538–552.

Hardee, J. E., Weiland, B. J., Nichols, T. E., Welsh, R. C., Soules, M. E., Steinberg, D. B., ···Heitzeg, M. M. (2014). Development of impulse control circuitry in children of alcoholics. *Biological Psychiatry*, 76(9), 708–716.

He, Q., Chen, M., Chen, C., Xue, G., Feng, T. & Bechara, A. (2016). Anodal stimulation of the left DLPFC increases IGT scores and decreases delay discounting rate in healthy males. *Frontiers in Psychology*, 7, 1421.

Hill, A. T., Rogasch, N. C., Fitzgerald, P. B. & Hoy, K. E. (2018). Effects of single versus dual-site high-definition transcranial direct current stimulation (HD-tDCS) on cortical reactivity and working memory performance in healthy subjects. *Brain Stimulation*, 11(5), 1033–1043.

Hogeveen, J., Grafman, J., Aboseria, M., David, A., Bikson, M. & Hauner, K. K. (2016). Effects of high-definition and conventional tDCS on response inhibition. *Brain Stimulation*, 9(5), 720–729.

Hsieh, S. & Lin, Y.-C. (2017). Stopping ability in younger and older adults: Behavioral and event-related potential. *Cognitive Affective & Behavioral Neuroscience*, 17(2), 348–363.

Hsu, T. Y., Tseng, L. Y., Yu, J. X., Kuo, W. J., Hung, D. L., Tzeng, O. J., ··· Juan, C. H. (2011). Modulating inhibitory control with direct current stimulation of the superior medial frontal cortex. *Neuroimage*, 56(4), 2249–2257.

Hughes, M., Fulham, W., Johnston, P. & Michie, P. (2012). Stop-signal response inhibition in schizophrenia: Behavioural, event-related potential and functional neuroimaging data. *Biological Psychology*, 89(1), 220–231.

Hwang, J., Kim, S., Park, C., Bang, S. & Kim, S. (2010). Acute high-frequency rTMS of the left dorsolateral prefrontal cortex and attentional control in healthy young men. *Brain Research*, 1329, 152–158.

Jacobson, L., Javitt, D. C. & Lavidor, M. (2011). Activation of inhibition: Diminishing impulsive behavior by direct current stimulation over the inferior frontal gyrus. *Journal of Cognitive Neuroscience*, 23(11), 3380–3387.

Jahfari, S., Waldorp, L., van den Wildenberg, W., Scholte, H., Ridderinkhof, K. & Forstmann, B. (2011). Effective connectivity reveals important roles for both the hyperdirect (fronto-subthalamic) and the indirect (fronto-striatal-pallidal) fronto-basal ganglia pathways during response inhibition. *Journal of Neuroscience*, 31(18), 6891–6899.

Juan, C. H. & Muggleton, N. G. (2012). Brain stimulation and inhibitory control. *Brain Stimulation*, 5(2), 63-69.

Ke, Y., Wang, N., Du, J., Kong, L., Liu, S., Xu, M., ···Ming, D. (2019). The effects of transcranial direct current stimulation (tDCS) on working memory training in healthy young adults. *Frontiers in Human Neuroscience*, 13, 19.

Kerr-German, A., Namuth, A., Santosa, H., Buss, A. T. & White, S. (2022). To snack or not to snack: Using fNIRS to link inhibitory control to functional connectivity in the toddler brain. *Developmental Science*, e13229.

Kessler, S., Turkeltaub, P., Benson, J. & Hamilton, R. (2012). Differences in the experience of active and sham transcranial direct current stimulation. *Brain Stimulation*, 5(2), 155–162.

Khaleghi, A., Jahromi, G. P., Zarafshan, H., Mostafavi, S. A. & Mohammadi, M. R. (2020). Effects of transcranial direct current stimulation of prefrontal cortex on risk-taking behavior. *Psychiatry and Clinical Neurosciences*, 74(9), 455–465.

Kohl, S., Hannah, R., Rocchi, L., Nord, C. L., Rothwell, J. & Voon, V. (2019). Cortical paired associative stimulation influences response inhibition: Cortico-cortical and cortico-subcortical networks. *Biological Psychiatry*, 85(4), 355–363.

Kringelbach, M. & Rolls, E. (2004). The functional neuroanatomy of the human orbitofrontal cortex: Evidence from neuroimaging and neuropsychology.

Progress in Neurobiology, 72(5), 341–372.

Krishnan, C., Santos, L., Peterson, M. & Ehinger, M. (2015). Safety of noninvasive brain stimulation in children and adolescents. *Brain Stimulation*, 8(1), 76–87.

Kumar, S., Zomorrodi, R., Ghazala, Z., Goodman, M. S., Blumberger, D. M., Cheam, A., ···Rajji, T. K. (2017). Extent of dorsolateral prefrontal cortex plasticity and its association with working memory in patients with alzheimer disease. *JAMA Psychiatry*, 74(12), 1266–1274.

Kuo, H.-I., Bikson, M., Datta, A., Minhas, P., Paulus, W., Kuo, M.-F. & Nitsche, M. A. (2013). Comparing cortical plasticity induced by conventional and high-definition 4 x 1 ring tDCS: A neurophysiological study. *Brain Stimulation*, 6(4), 644–648.

Kwon, Y. H. & Kwon, J. W. (2013a). Is transcranial direct current stimulation a potential method for improving response inhibition? *Neural Regeneration Research*, 8(11), 1048–1054.

Kwon, Y. H. & Kwon, J. W. (2013b). Response inhibition induced in the stop-signal task by transcranial direct current stimulation of the pre-supplementary motor area and primary sensoriomotor cortex. *Journal of Physical Therapy Science*, 25(9), 1083–1086.

Lapenta, O., Sierve, K., de Macedo, E., Fregni, F. & Boggio, P. (2014). Transcranial direct current stimulation modulates ERP-indexed inhibitory control and reduces food consumption. *Appetite*, 83, 42–48.

Leite, J., Goncalves, O. F., Pereira, P., Khadka, N., Bikson, M., Fregni, F. & Carvalho, S. (2018). The differential effects of unihemispheric and bihemispheric tDCS over the inferior frontal gyrus on proactive control. *Neuroscience Research*, 130, 39–46.

Li, B., Nguyen, T. P., Ma, C. & Dan, Y. (2020). Inhibition of impulsive action by projection-defined prefrontal pyramidal neurons. *Proceedings of the National Academy of Sciences of the United States of America*, 117(29), 17278–17287.

Li, L. M., Violante, I. R., Leech, R., Hampshire, A., Opitz, A., McArthur, D., ···Sharp, D. J. (2019). Cognitive enhancement with salience network electrical stimulation is influenced by network structural connectivity. *Neuroimage*, 185, 425–433.

Liang, W. K., Lo, M. T., Yang, A. C., Peng, C. K., Cheng, S. K., Tseng, P. & Juan, C. H. (2014). Revealing the brain' s adaptability and the transcranial direct current stimulation facilitating effect in inhibitory control by multiscale entropy. *Neuroimage*, 90, 218–234.

Lofredi, R., Auernig, G., Irmen, F., Nieweler, J., Neumann, W., Horn, A., . . . Kühn, A. (2021). Subthalamic stimulation impairs stopping of ongoing movements. *Brain*, 144(1), 44–52.

Lu, H., Gong, Y., Huang, P., Zhang, Y., Guo, Z., Zhu, X. & You, X. (2020). Effect of repeated anodal HD-tDCS on executive functions: Evidence from a pilot and single-blinded fNIRS study. *Frontiers in Human Neuroscience*, 14, 583730.

Lu, H., Liu, Q., Guo, Z., Zhou, G., Zhang, Y., Zhu, X. & Wu, S. (2020). Modulation of repeated anodal HD-tDCS on attention in healthy young adults. *Frontiers in Psychology*, 11, 564447.

Mahmood, O., Goldenberg, D., Thayer, R., Migliorini, R., Simmons, A. & Tapert, S. (2013). Adolescents' fMRI activation to a response inhibition task predicts future substance use. *Addictive Behaviors*, 38(1), 1435–1441.

Mansouri, F., Acevedo, N., Illipparampil, R., Fehring, D., Fitzgerald, P. & Jaberzadeh, S. (2017). Interactive effects of music and prefrontal cortex stimulation in modulating response inhibition. *Scientific Reports*, 7(1), 18096.

Manuel, A., Grivel, J., Bernasconi, F., Murray, M. & Spierer, L. (2010). Brain dynamics underlying training-induced improvement in suppressing inappropriate action. *Journal of Neuroscience*, 30(41), 13670–13678.

Martin, A. K., Kessler, K., Cooke, S., Huang, J. & Meinzer, M. (2020). The right temporoparietal junction is causally associated with embodied perspective-taking. *Journal of Neuroscience*, 40(15), 3089–3095.

Mayer, J. T., Chopard, G., Nicolier, M., Gabriel, D., Masse, C., Giustiniani, J., ···Bennabi, D. (2020). Can transcranial direct current stimulation (tDCS) improve impulsivity in healthy and psychiatric adult populations? A systematic review. *Progress in Neuro-psychopharmacology & Biological Psychiatry*, 98, 109818.

Meinzer, M., Jahnigen, S., Copland, D. A., Darkow, R., Grittner, U., Avirame, K., ···Floel, A. (2014). Transcranial direct current stimulation over multiple days improves learning and maintenance of a novel vocabulary. *Cortex*, 50, 137–147.

Nejati, V., Rasanan, A. H. H., Rad, J. A., Alavi, M. M., Haghi, S. & Nitsche, M. A. (2021). Transcranial direct current stimulation (tDCS) alters the pattern of information processing in children with ADHD: Evidence from drift diffusion modeling. *Neurophysiologie Clinique-Clinical Neurophysiology*, 52(1), 17–27.

Nejati, V., Salehinejad, M. & Nitsche, M. (2018). Interaction of the left dorsolateral prefrontal cortex (l-DLPFC) and right orbitofrontal cortex (OFC) in hot and cold executive functions: Evidence from transcranial direct current stimulation (tDCS). *Neuroscience*, 369, 109–123.

Neubert, F., Mars, R., Buch, E., Olivier, E. & Rushworth, M. (2010). Cortical and subcortical interactions during action reprogramming and their related white matter pathways. *Proceedings of the National Academy of Sciences of the United States of America*, 107(30), 13240–13245.

Nieratschker, V., Kiefer, C., Giel, K., Kruger, R. & Plewnia, C. (2015). The COMT Val/Met polymorphism modulates effects of tDCS on response inhibition. *Brain Stimulation*, 8(2), 283–288.

Nikolin, S., Loo, C. K., Bai, S., Dokos, S. & Martin, D. M. (2015). Focalised stimulation using high definition transcranial direct current stimulation (HD-tDCS) to investigate declarative verbal learning and memory functioning. *Neuroimage*, 117, 11–19.

Nitsche, M. A., Cohen, L. G., Wassermann, E. M., Priori, A., Lang, N., Antal, A., . . . Pascual-Leone, A. (2008). Transcranial direct current stimulation: State of the art 2008. *Brain Stimulation*, 1(3), 206–223.

Nitsche, M. & Paulus, W. (2001). Sustained excitability elevations induced by transcranial DC motor cortex stimulation in humans. *Neurology*, 57(10), 1899–1901.

Nitsche, M. A. & Paulus, W. (2000). Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *The Journal of Physiology*, 527 Pt 3, 633–639.

Nowak, D. A., Hoffmann, U., Connemann, B. J. & Schonfeldt-Lecuona, C. (2006). Epileptic seizure following 1 Hz repetitive transcranial magnetic stimulation. *Clinical neurophysiology*, 117(7), 1631–1633.

O' Connell, N. E., Wand, B. M., Marston, L., Spencer, S. & Desouza, L. H. (2014). Non-invasive brain stimulation techniques for chronic pain. *Cochrane Database of Systematic Reviews*, 3(3), CD008208.

Obeso, I., Robles, N., Marrón, E. & Redolar-Ripoll, D. (2013). Dissociating the role of the pre-SMA in response inhibition and switching: A combined online and offline TMS approach. *Frontiers in Human Neuroscience*, 7, 360.

Oosterlaan, J., Logan, G. & Sergeant, J. (1998). Response inhibition in AD/HD, CD, comorbid AD/HD + CD, anxious, and control children: A meta-analysis of studies with the stop task. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, 39(3), 411–425.

Ordaz, S. J., Foran, W., Velanova, K. & Luna, B. (2013). Longitudinal growth curves of brain function underlying inhibitory control through adolescence. *Journal of Neuroscience*, 33(46), 18109–18124.

Osada, T., Ogawa, A., Suda, A., Nakajima, K., Tanaka, M., Oka, S., . . . Konishi, S. (2021). Parallel cognitive processing streams in human prefrontal cortex: Parsing areal-level brain network for response inhibition. *Cell Reports*, 36(12), 109732–109732.

Paneri, B., Adair, D., Thomas, C., Khadka, N., Patel, V., Tyler, W. J., ··· Bikson, M. (2016). Tolerability of repeated application of transcranial electrical stimulation with limited outputs to healthy subjects. *Brain Stimulation*, 9(5), 740–754.

Pisoni, A., Mattavelli, G., Papagno, C., Rosanova, M., Casali, A. G. & Romero Lauro, L. J. (2018). Cognitive enhancement induced by anodal tDCS drives circuit-specific cortical plasticity. *Cerebral Cortex*, 28(4), 1132–1140.

Plewnia, C., Zwissler, B., Längst, I., Maurer, B., Giel, K. & Krüger, R. (2013). Effects of transcranial direct current stimulation (tDCS) on executive functions: Influence of COMT Val/Met polymorphism. *Cortex*, 49(7), 1801–1807.

Rae, C., Hughes, L., Anderson, M. & Rowe, J. (2015). The prefrontal cortex achieves inhibitory control by facilitating subcortical motor pathway connectivity. *Journal of neuroscience*, 35(2), 786–794.

Rossi, S., Antal, A., Bestmann, S., Bikson, M., Brewer, C., Brockmoller, J., . . . Hallett, M. (2021). Safety and recommendations for TMS use in healthy subjects and patient populations, with updates on training, ethical and regulatory issues: Expert guidelines. *Clinical Neurophysiology*, 132(1), 269–306.

Sampaio-Junior, B., Tortella, G., Borrione, L., Moffa, A. H., Machado-Vieira, R., Cretaz, E., ···Brunoni, A. R. (2018). Efficacy and safety of transcranial direct current stimulation as an add-on treatment for bipolar depression: A randomized clinical trial. *JAMA Psychiatry*, 75(2), 158–166.

Sandrini, M., Xu, B., Volochayev, R., Awosika, O., Wang, W., Butman, J. & Cohen, L. (2020). Transcranial direct current stimulation facilitates response inhibition through dynamic modulation of the fronto-basal ganglia network. *Brain Stimulation*, 13(1), 96–104.

Schachar, R., Crosbie, J., Barr, C., Ornstein, T., Kennedy, J., Malone, M., ··· Pathare, T. (2005). Inhibition of motor responses in siblings concordant and discordant for attention deficit hyperactivity disorder. *American Journal of Psychiatry*, 162(6), 1076–1082.

Schroeder, P., Schwippel, T., Wolz, I. & Svaldi, J. (2020). Meta-analysis of the effects of transcranial direct current stimulation on inhibitory control. *Brain Stimulation*, 13(5), 1159–1167.

Sedgmond, J., Lawrence, N. S., Verbruggen, F., Morrison, S., Chambers, C. D. & Adams, R. C. (2019). Prefrontal brain stimulation during food-related inhibition training: Effects on food craving, food consumption and inhibitory control. *Royal Society Open Science*, 6(1), 15.

Sharp, D. J., Bonnelle, V., De Boissezon, X., Beckmann, C. F., James, S. G., Patel, M. C. & Mehta, M. A. (2010). Distinct frontal systems for response inhibition, attentional capture, and error processing. *Proceedings of the National Academy of Sciences of the United States of America*, 107(13), 6106–6111.

Shen, B., Yin, Y., Wang, J., Zhou, X., McClure, S. M. & Li, J. (2016). High-definition tDCS alters impulsivity in a baseline-dependent manner. *Neuroimage*, 143, 343–352.

Stagg, C., Best, J., Stephenson, M., O' Shea, J., Wylezinska, M., Kincses, Z., ···

Johansen-Berg, H. (2009). Polarity-sensitive modulation of cortical neurotransmitters by transcranial stimulation. *Journal of neuroscience*, 29(16), 5202–5206.

Stagg, C. J. & Nitsche, M. A. (2011). Physiological basis of transcranial direct current stimulation. *Neuroscientist*, 17(1), 37–53.

Steele, V., Fink, B., Maurer, J., Arbabshirani, M., Wilber, C., Jaffe, A., ··· Kiehl, K. (2014). Brain potentials measured during a Go/NoGo task predict completion of substance abuse treatment. *Biological Psychiatry*, 76(1), 75–83.

Stramaccia, D. F., Penolazzi, B., Sartori, G., Braga, M., Mondini, S. & Galfano, G. (2015). Assessing the effects of tDCS over a delayed response inhibition task by targeting the right inferior frontal gyrus and right dorsolateral prefrontal cortex. *Experimental Brain Research*, 233(8), 2283–2290.

Sun, J. B., Tian, Q. Q., Yang, X. J., Deng, H., Li, N., Meng, L. X., ···Qin, W. (2021). Synergistic effects of simultaneous transcranial direct current stimulation (tDCS) and transcutaneous auricular vagus nerve stimulation (taVNS) on the brain responses. *Brain Stimulation*, 14(2), 417–419.

Swann, N. C., Cai, W., Conner, C. R., Pieters, T. A., Claffey, M. P., George, J. S., . . . Tandon, N. (2012). Roles for the pre-supplementary motor area and the right inferior frontal gyrus in stopping action: Electrophysiological responses and functional and structural connectivity. *Neuroimage*, 59(3), 2860–2870.

Tan, J., Iyer, K. K., Tang, A. D., Jamil, A., Martins, R. N., Sohrabi, H. R., ···Fujiyama, H. (2019). Modulating functional connectivity with non-invasive brain stimulation for the investigation and alleviation of age-associated declines in response inhibition: A narrative review. *Neuroimage*, 185, 490–512.

Thakkar, K. N., Schall, J. D., Boucher, L., Logan, G. D. & Park, S. (2011). Response inhibition and response monitoring in a saccadic countermanding task in schizophrenia. *Biological Psychiatry*, 69(1), 55-62.

Thunberg, C., Messel, M. S., Raud, L. & Huster, R. J. (2020). tDCS over the inferior frontal gyri and visual cortices did not improve response inhibition. *Scientific Reports*, 10(1), 7749.

Turski, C. A., Kessler-Jones, A., Chow, C., Hermann, B., Hsu, D., Jones, J., ···Ikonomidou, C. (2017). Extended multiple-field high-definition transcranial direct current stimulation (HD-tDCS) is well tolerated and safe in healthy adults. *Restorative Neurology and Neuroscience*, 35(6), 631–642.

Valiengo, L., Goerigk, S., Gordon, P. C., Padberg, F., Serpa, M. H., Koebe, S., ···Brunoni, A. R. (2020). Efficacy and safety of transcranial direct current stimulation for treating negative symptoms in schizophrenia: A randomized clinical trial. *JAMA Psychiatry*, 77(2), 121–129.

van Rooij, D., Hoekstra, P. J., Mennes, M., von Rhein, D., Thissen, A. J., Heslenfeld, D., ···Hartman, C. A. (2015). Distinguishing adolescents with ADHD

from their unaffected siblings and healthy comparison subjects by neural activation patterns during response inhibition. *American Journal of Psychiatry*, 172(7), 674-683.

Verbruggen, F., Aron, A. R., Band, G. P. H., Beste, C., Bissett, P. G., Brockett, A. T., . . . Boehler, C. N. (2019). A consensus guide to capturing the ability to inhibit actions and impulsive behaviors in the stop-signal task. *eLife*, 8, e46323.

Verbruggen, F. & Logan, G. D. (2008). Response inhibition in the stop-signal paradigm. *Trends in Cognitive Sciences*, 12(11), 418-424.

Verbruggen, F. & Logan, G. D. (2009). Models of response inhibition in the stop-signal and stop-change paradigms. *Neuroscience and Biobehavioral Reviews*, 33(5), 647-661.

Villamar, M. F., Wivatvongvana, P., Patumanond, J., Bikson, M., Truong, D. Q., Datta, A. & Fregni, F. (2013). Focal modulation of the primary motor cortex in fibromyalgia using 4x1-ring high-definition transcranial direct current stimulation (HD-tDCS): Immediate and delayed analgesic effects of cathodal and anodal stimulation. *Journal of Pain*, 14(4), 371-383.

Weidacker, K., Weidemann, C. T., Boy, F. & Johnston, S. J. (2016). Cathodal tDCS improves task performance in participants high in coldheartedness. *Clinical Neurophysiology*, 127(9), 3102-3109.

Weidler, C., Habel, U., Wallheinke, P., Wagels, L., Hofhansel, L., Ling, S., ··· Clemens, B. (2020). Consequences of prefrontal tDCS on inhibitory control and reactive aggression. *Social Cognitive and Affective Neuroscience*, 17(1), 120-130.

Wessel, J. R. (2018). Surprise: A more realistic framework for studying action stopping? *Trends in Cognitive Sciences*, 22(9), 741-744.

Wessel, M. J., Park, C. H., Beanato, E., Cuttaz, E. A., Timmermann, J. E., Schulz, R., ···Hummel, F. C. (2021). Multifocal stimulation of the cere-cerebellar loop during the acquisition of a novel motor skill. *Scientific Reports*, 11(1), 1756.

Woods, A. J., Antal, A., Bikson, M., Boggio, P. S., Brunoni, A. R., Celnik, P., . . . Nitsche, M. A. (2016). A technical guide to tDCS, and related non-invasive brain stimulation tools. *Clinical Neurophysiology*, 127(2), 1031-1048.

Wu, D., Zhou, Y., Xu, P., Liu, N., Sun, K. & Xiao, W. (2021). Initial performance modulates the effects of cathodal transcranial direct current stimulation (tDCS) over the right dorsolateral prefrontal cortex on inhibitory control. *Brain Research*, 1774, 147722.

Xu, P., Wu, D., Chen, Y., Wang, Z. & Xiao, W. (2020). The effect of response inhibition training on risky decision-making task performance. *Frontiers in Psychology*, 11, 1806.

Yavari, F., Jamil, A., Samani, M. M., Vidor, L. P. & Nitsche, M. A. (2018). Basic and functional effects of transcranial electrical stimulation (tES)-an introduction. *Neuroscience and Biobehavioral Reviews*, 85, 81-92.

Yu, J., Tseng, P., Hung, D. L., Wu, S. W. & Juan, C. H. (2015). Brain stimulation improves cognitive control by modulating medial-frontal activity and preSMA-vmPFC functional connectivity. *Human Brain Mapping*, 36(10), 4004–4015.

Zandbelt, B., Bloemendaal, M., Hoogendam, J., Kahn, R. & Vink, M. (2013). Transcranial magnetic stimulation and functional MRI reveal cortical and subcortical interactions during stop-signal response inhibition. *Journal of Cognitive Neuroscience*, 25(2), 157–174.

Zandbelt, B., van Buuren, M., Kahn, R. & Vink, M. (2011). Reduced proactive inhibition in schizophrenia is related to corticostriatal dysfunction and poor working memory. *Biological Psychiatry*, 70(12), 1151–1158.

Zewdie, E., Ciechanski, P., Kuo, H. C., Giuffre, A., Kahl, C., King, R., ··· Kirton, A. (2020). Safety and tolerability of transcranial magnetic and direct current stimulation in children: Prospective single center evidence from 3.5 million stimulations. *Brain Stimulation*, 13(3), 565–575.

Zhou, X., Planalp, E. M., Heinrich, L., Pletcher, C., DiPiero, M., Alexander, A. L., . . . Dean, D. C., 3rd. (2021). Inhibitory control in children 4-10 years of age: Evidence from functional near-infrared spectroscopy task-based observations. *Frontiers in Human Neuroscience*, 15, 798358.

Note: Figure translations are in progress. See original paper for figures.