Brain Stimulation 9 (2016) 720–729

Contents lists available at ScienceDirect

Brain Stimulation

journal homepage: www.brainstimjrnl.com

Effects of High-Definition and Conventional tDCS on Response Inhibition

J. Hogeveen [a,b,*], J. Grafman [a,b,c], M. Aboseria [d], A. David [d], M. Bikson [d], K.K. Hauner [a,b,c]

[a] Cognitive Neuroscience Laboratory, Rehabilitation Institute of Chicago, Chicago, IL, USA
[b] Department of Physical Medicine and Rehabilitation, Feinberg School of Medicine, Northwestern University, Chicago, IL, USA
[c] Department of Neurology, Feinberg School of Medicine, Northwestern University, Chicago, IL, USA
[d] Department of Biomedical Engineering, The City College of New York, New York, NY, USA

ARTICLE INFO

Article history:
Received 1 October 2015
Received in revised form 8 April 2016
Accepted 16 April 2016
Available online 22 April 2016

Keywords:
Transcranial direct current stimulation
HD-tDCS
Response inhibition
Inferior frontal cortex
Computational neurostimulation

ABSTRACT

Background: Response inhibition is a critical executive function, enabling the adaptive control of behavior in a changing environment. The inferior frontal cortex (IFC) is considered to be critical for response inhibition, leading researchers to develop transcranial direct current stimulation (tDCS) montages attempting to target the IFC and improve inhibitory performance. However, conventional tDCS montages produce diffuse current through the brain, making it difficult to establish causality between stimulation of any one given brain region and resulting behavioral changes. Recently, high-definition tDCS (HD-tDCS) methods have been developed to target brain regions with increased focality relative to conventional tDCS.
Objective: Remarkably few studies have utilized HD-tDCS to improve cognitive task performance, however, and no study has directly compared the behavioral effects of HD-tDCS to conventional tDCS.
Methods: In the present study, participants received either HD-tDCS or conventional tDCS to the IFC during performance of a response inhibition task (stop-signal task, SST) or a control task (choice reaction time task, CRT). A third group of participants completed the same behavioral protocols, but received tDCS to a control site (mid-occipital cortex). Post-stimulation improvement in SST performance was analyzed as a function of tDCS group and the task performed during stimulation using both conventional and Bayesian parameter estimation analyses.
Results: Bayesian estimation of the effects of HD- and conventional tDCS to IFC relative to control site stimulation demonstrated enhanced response inhibition for both conditions. No improvements were found after control task (CRT) training in any tDCS condition.
Conclusion: Results support the use of both HD- and conventional tDCS to the IFC for improving response inhibition, providing empirical evidence that HD-tDCS can be used to facilitate performance on an executive function task.

Introduction

The human brain is capable of rapidly implementing a vast array of behavioral responses, yet this ability would be ill-suited to the real world without the capacity to stop responses that become irrelevant or inappropriate following changes in the environment [1]. This process, known as *response inhibition*, is critical to the executive control of behavior, and research aimed at identifying its neural substrates has received growing attention in recent years [2,3]. Functional magnetic resonance imaging (fMRI) studies have identified a consistent network of brain regions that are engaged during response inhibition tasks, including pre-supplementary motor area (preSMA), inferior frontal cortex (IFC), and the subthalamic nucleus (STN) of the basal ganglia [4–7]. The present study focuses on the IFC, which has been suggested to represent the key "brake" node in the response inhibition network, implementing the signal required to inhibit the performance of a planned response [2,3].

Neuropsychological evidence has consistently linked inhibitory control function to regions of the prefrontal cortex [8,9]. Supporting the view that the IFC is necessary for response inhibition, studies in patients with prefrontal brain lesions have shown that damage to this region impairs one's ability to refrain from either initiating a prepotent behavioral response [10] or stopping an ongoing response [11]. Furthermore, a causal role of the IFC in

* Corresponding author. Tel.: +17739412182; fax: +13122382208.
E-mail address: jeremy.hogeveen@northwestern.edu (J. Hogeveen).

1935-861X/
http://dx.doi.org/10.1016/j.brs.2016.04.015

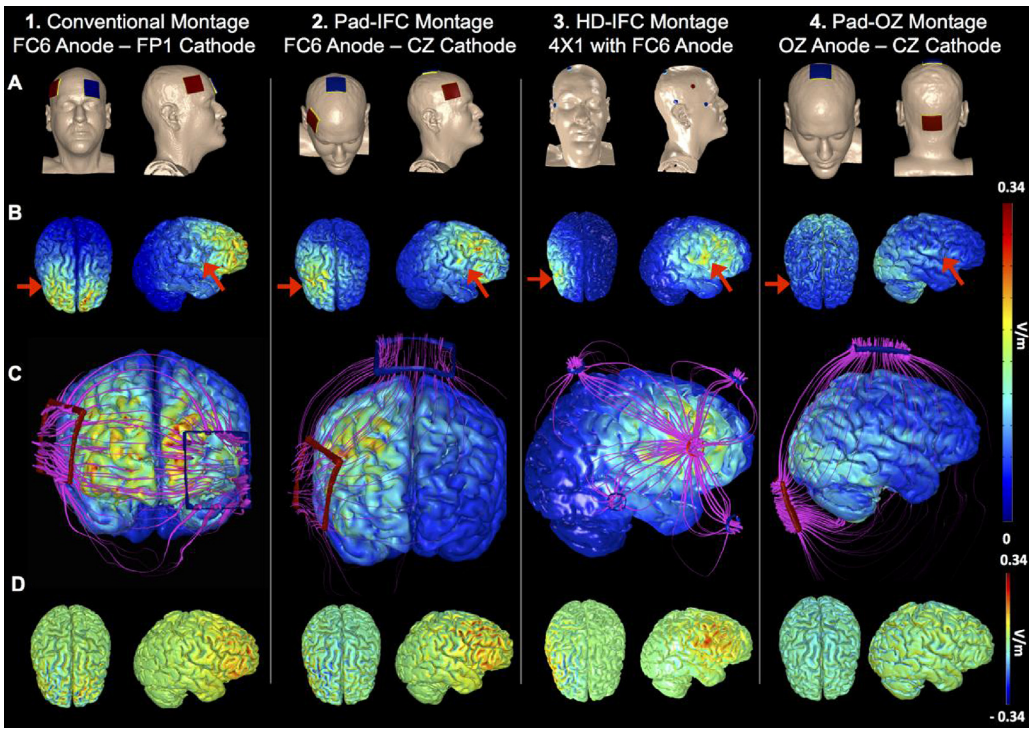

Figure 1. Computational neurostimulation models predict patterns of excitation induced by each of the tDCS montages (columns 1–4). A) Montages used in computational forward modeling displaying position of tDCS electrodes (red is anode and blue is cathode). B) Plot of electric field magnitude on cortical surface (scale 0: blue to ≥0.34 V/m: red). Red arrows approximately mark the IFC target region. Note the different brain current flow patterns and targetings predicted from montages in columns 1–4. C) Violet streamlines representing current flow through gray matter in each of the four montages. D) Plot of radial electric field component distribution across cortical surface with inward (nominally excitatory) current positive and outward (nominally inhibitory) current negative (scale ≤0.34: blue, 0: green, ≥0.34: red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

response inhibition has been reaffirmed by using transcranial magnetic stimulation (TMS) to disturb IFC function and impair response inhibition [12,13]. Since disturbed IFC recruitment during response inhibition is a hallmark of several psychiatric and neurological disorders [14–16], studies that aim to promote regional activity in this area of the brain may offer promising new developments in the treatment of these conditions.

One promising method for enhancing regional brain activity is transcranial direct current stimulation (tDCS [17]). In conventional tDCS protocols, a mild electrical current (≈1–2 mA) is passed between two large electrode pads (≈25–35 cm^2) placed in different arrangements on the scalp (electrode montage). One of the electrodes is an anode and the other is a cathode, and >10 minutes of tDCS delivery has been found to increase the excitability of cortical structures near the anode for as long as 90 minutes post-stimulation [18,19]. Critically, this enhanced neuronal excitability has been associated with improvements in cognitive functions associated with structures nearer to the anodal electrode site. For example, tDCS with the anodal pad placed over the parietal cortex has been associated with improved performance on spatial attention and numerosity tasks [20–23], whereas stimulation with the anode over prefrontal cortex has been shown to modulate planning [24], decision-making [25,26], social reasoning [27], and working memory [28,29]. Of particular relevance to the present study, researchers have started to investigate prefrontal tDCS as a tool for improving response inhibition.

Specifically, recent studies have demonstrated improved response inhibition following conventional tDCS with an anode placed over right IFC or pre-supplementary motor area (preSMA) and the cathodal electrode placed on the opposite side of the head [30–33]. Given the well-established role of right IFC and preSMA in response inhibition [2,3], the studies' authors argued that enhanced excitability at the structures underneath the anodal pad drove the observed behavioral improvement. However, computational neurostimulation[1] studies have suggested that pad tDCS produces diffuse current through the brain including both cortical and deep structures (Fig. 1.1–2,4; [34–36]). This diffuse pattern of current flow is supported by evidence from combined tDCS/fMRI studies [37,38], thereby making it difficult to establish causality between modulated activity at the nominal target site and resulting behavioral changes [39–41].

In an effort to improve the spatial focality of tDCS, researchers have recently developed high-definition tDCS (HD-tDCS) delivery systems [34,35]. Typically, HD-tDCS involves passing a small direct electrical current (again, typically 1–2 mA) through a 4×1 montage of stimulating electrodes (1 cm diameter), with a single anodal electrode placed over the target brain region, and four return electrodes arranged in a ring surrounding the anode, each receiving 25% of the return current. Computational neurostimulation studies suggest that the focality of HD-tDCS is far superior to conventional tDCS, with current flow restricted to the circumscribed ring (Fig. 1.3) [35,42]. The efficacy of HD-tDCS for inducing neurophysiological changes has been established in research on human motor system activity, by applying anodal stimulation over the primary motor cortex and demonstrating subsequent increases in corticospinal excitability [43,44].

Although such findings in the domain of motor excitation have been established and replicated, similar effects in non-motor domains

[1] "Biologically plausible models and/or neural networks that simulate the consequences of neurostimulation." [39]