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Research report

Transcranial direct current stimulation (tDCS) of frontal cortex decreases performance on the WAIS-IV intelligence test

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HIGHLIGHTS

- Anodal tDCS over DLPFC reduced performance on the WAIS-IV.
- Reduced practice gains were found for right, left, and bilateral tDCS over DLPFC.
- Impairment was specific to perceptual reasoning.

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ABSTRACT

Transcranial direct current stimulation (tDCS) modulates excitability of motor cortex. However, there is conflicting evidence about the efficacy of this non-invasive brain stimulation modality to modulate performance on cognitive tasks. Previous work has tested the effect of tDCS on specific facets of cognition and executive processing. However, no randomized, double-blind, sham-controlled study has looked at the effects of tDCS on a comprehensive battery of cognitive processes. The objective of this study was to test if tDCS had an effect on performance on a comprehensive assay of cognitive processes, a standardized intelligence quotient (IQ) test. The study consisted of two substudies and followed a double-blind, between-subjects, sham-controlled design. In total, 41 healthy adult participants were included in the final analysis. These participants completed the Wechsler Adult Intelligence Scale, Fourth Edition (WAIS-IV) as a baseline measure. At least one week later, participants in substudy 1 received either bilateral tDCS (anodes over both F4 and F3, cathode over Cz, 2 mA at each anode for 20 min) or active sham tDCS (2 mA for 40 s), and participants in substudy 2 received either right or left tDCS (anode over either F4 or F3, cathode over Cz, 2 mA for 20 min). In both studies, the WAIS-IV was immediately administered following stimulation to assess for performance differences induced by bilateral and unilateral tDCS. Compared to sham stimulation, right, left, and bilateral tDCS reduced improvement between sessions on Full Scale IQ and the Perceptual Reasoning Index. This demonstration that frontal tDCS selectively degraded improvement on specific metrics of the WAIS-IV raises important questions about the often proposed role of tDCS in cognitive enhancement.

Abbreviations: PFC, Prefrontal cortex; tDCS, transcranial direct current stimulation; IQ, intelligence quotient; WAIS-IV, Wechsler Adult Intelligence Scale, Fourth Edition; FSIQ, full scale IQ; VCI, Verbal Comprehension Index; PRI, Perceptual Reasoning Index; WMI, Working Memory Index; PSI, Processing Speed Index; tACS, transcranial alternating current stimulation; tDCS, transcranial direct current stimulation.

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1. Introduction

The importance of frontal brain regions has been demonstrated for numerous cognitive processes contributing to intelligence. Dorsolateral prefrontal cortex (DLPFC), a functional area in frontal cortex, is recruited during tests of general intelligence [1–4]. The middle frontal gyrus (the anatomical location of DLPFC) has been implicated in abstracting and integrating logical relationships [5], the ability to resolve interference efficiently [6], and visuospatial reasoning [7]. Medial of the middle frontal gyrus lies the superior frontal gyrus; the lateral part of the superior frontal gyrus has been implicated in aspects of fluid intelligence [8,9], while the medial portion contributes to the default mode network and exhibits deactivation and reduced blood flow during cognitive processing [10,11]. Patients with lesions to left superior frontal gyrus demonstrate deficits in working memory compared to controls, particularly in the spatial domain [12]. The most anterior portion of the frontal cortex, prefrontal cortex (PFC), is activated in a performance-dependent way during reasoning and novel problem-solving tests of fluid intelligence [13]. Spatial and verbal tasks requiring high general intelligence differentially increased activation of lateral PFC in comparison to control tasks [3].

Given the widespread involvement of frontal brain areas in higher-order cognitive processing, they represent an attractive target for modulating cognitive function. The ability to both improve cognitive performance in healthy individuals and to alleviate deficits in patients with neuropsychiatric illnesses is the goal of substantial research efforts. A growing body of work has been conducted using transcranial direct current stimulation (tDCS), a form of non-invasive brain stimulation, in an attempt to modulate cognitive abilities [14–16]. Anodal tDCS increases neural activity by depolarizing cortical neurons, whereas cathodal tDCS reduces neural activity by hyperpolarizing neurons [17,18]. Large neuronal networks are sensitive to such weak perturbations of neuronal membrane voltage caused by these electric fields [19–23]. Changes in neuronal excitability induced by tDCS outlast the duration of the stimulation [18], likely through the recruitment of BDNF-dependent plasticity [24–26].

The reported effects of tDCS on cognitive abilities are diverse, with seemingly conflicting reports of increased and decreased performance. The majority of studies conducted to date only used one behavioral assay to test a specific facet of cognitive processing. To our knowledge, no one study has conducted a comprehensive battery of cognitive testing with the same study population in order to assess the effects of tDCS on performance. Thus, we here asked if tDCS affects performance on a comprehensive assay of overall cognition, a standardized Intelligence Quotient (IQ) test. One of the most widely utilized IQ tests is the Wechsler Adult Intelligence Scale, Fourth Edition (WAIS-IV). Use of the WAIS-IV test is advantageous because separate index scores can be calculated to provide insight into more fine-grained components of intelligence. Previous work has suggested that the different aspects of intelligence probed by the WAIS-IV indices and subtests do not share a single common neuronal substrate [27].

Because of the broad activation of frontal areas, we first tested if bilateral tDCS over DLPFC changed performance on the WAIS-IV. We hypothesized that by targeting frontal areas with tDCS, we would induce improved performance. Interestingly, the effects of stimulation were detrimental to IQ test performance, specifically in tasks of perceptual reasoning. We then conducted a second study to test the effects of unilateral right or left tDCS on performance on the WAIS-IV; similar performance decreases were found with additional evidence for more pronounced decreases for right tDCS.

2. Materials and methods

2.1. Participants

In total, 44 healthy adults were recruited for this study (21 males, 23 females, mean age = 22.1 years, SD = 4.72 years) from the University of North Carolina at Chapel Hill community. The study was divided into two consecutive substudies for which participants were recruited separately. For substudy 1, 22 participants participated in Session 1 of IQ testing, and 21 of these participants returned for Session 2 and received either bilateral tDCS or sham tDCS with subsequent repeat IQ testing. One participant could not be contacted for Session 2 and was therefore excluded from the study. For substudy 2, 22 participants completed Session 1 of IQ testing, and 20 of these participants returned for Session 2 and received either right tDCS (anodal electrode on right hemisphere) or left tDCS (anodal electrode on left hemisphere) with subsequent repeat IQ testing. Analysis was conducted on the 20 participants who completed both sessions. No participants took part in both substudy 1 and substudy 2. By self-report, participants did not have a history of neurologic or psychiatric illness, were not currently using medication for a neurologic or psychiatric illness, were not currently undergoing counseling or psychotherapy treatment, did not have a first degree relative with a neurologic or psychiatric condition, had never undergone brain surgery, had no brain devices/implants, did not have any cardiovascular diseases, and were not pregnant. All participants signed written consent prior to participation. This study was approved by the UNC–Chapel Hill IRB.

2.2. Experimental design

Both substudy 1 and substudy 2 followed a double-blind, between-subjects design with repeated-measure testing of IQ. In both substudies, participants completed the full WAIS-IV (Pearson Education, Inc., San Antonio, TX), as detailed below during the initial study visit (Session 1, baseline). Participants returned at least one week later (Session 2, mean time between sessions = 23.6 days, SD = 19.7) and received either sham or bilateral tDCS (Substudy 1, Fig. 3A) or right or left tDCS (substudy 2, Fig. 3B) and immediately afterwards completed the same WAIS-IV test. At the conclusion of the Session 2, participants completed a questionnaire asking if they believed they received stimulation.

2.3. Wechsler Adult Intelligence Scale, Fourth Edition (WAIS-IV)

The WAIS-IV is a comprehensive clinical instrument for assessing intelligence of adults between the ages of 16–90 years. There has been substantial demonstration of the test's validity and reliability. The test is composed of 15 core and supplemental subtests which contribute to a composite score that represents general intellectual ability (full scale IQ, FSIQ) and scores in indices of specific cognitive areas. While the FSIQ is considered the best measure of overall cognitive ability, the test issuer recommends to further report the index scales that all contribute to the FSIQ: Verbal Comprehension Index (VCI), Perceptual Reasoning Index (PRI), Working Memory Index (WMI), and Processing Speed Index (PSI). The VCI measures verbal reasoning, verbal concept formation, and knowledge acquired from the environment [28]. Strategies to solve the problems presented in this index may also utilize nonverbal factors such as forming mental pictures. The PRI measures perceptual and fluid reasoning, spatial processing, and visual-motor integration [29]. The WMI measures working memory, the ability to temporarily hold information in memory, manipulate or perform a mental operation on this information, and produce a response [29]; these processes require attention, concentration, mental control, and