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Does the Direction of Current Flow Using Transcranial Direct-Current Stimulation (tDCS) Affect One's Ability to Perform Motor Tasks?

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Does the Direction of Current Flow Using Transcranial Direct-Current Stimulation (tDCS)
Affect One's Ability to Perform Motor Tasks?

Senior Project Submitted to

The Division of Science, Mathematics, and Computing

Bard College

by

Zongheng Zhang

Annandale-on-Hudson, New York

May 2020

Acknowledgments

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“I've seen things you people wouldn't believe...

Attack ships on fire off the shoulder of Orion...

I watched C-beams glitter in the dark near the Tannhäuser Gate...

All those moments will be lost in time...

like tears in rain...

Time to die...”

Roy, *Blade Runner* (1982)

Glossary of Abbreviations

tDCS : Transcranial Direct Current Stimulation

EEG : Electroencephalography

FTT : Finger-Tapping Task

RT : Reaction Time

ACC : Accuracy

MEP : Motor Evoked Potential

DLPFC : Dorsolateral Prefrontal Cortex

TMS: Transcranial Magnetic Stimulation

Abstract

Transcranial direct-current stimulation (tDCS), is a non-invasive, painless brain stimulation treatment that uses direct electrical currents to stimulate specific parts of the brain. This is achieved by placing two electrodes--one positive (the anode) and one negative (the cathode)--on the scalp and running current across them. Altering the cortical excitability in this manner has been associated with changes in a variety of cognitive and motor tasks, those thought to be controlled by the underlying regions. While most of the existing literature has focused on the effects of placing the anode over the target region (often benefitting the associated performance), there is some evidence suggesting that switching the polarity and placing the cathode over the target region reverses the behavioral effect, such that an improvement might turn into a decrement.

For my Senior Project, I conducted an experiment manipulating the polarity of the electrode placed over my target region of interest (the left dorsolateral prefrontal cortex (L DLPFC) in order to test whether cathodal stimulation temporarily impairs motor skill performance. As far as I am aware, all previous tDCS work targeting this region has focused exclusively on anodal stimulation as it pertains to motor skill performance. I compared the accuracy and reaction times involved in a standard motor task (using a finger-tapping task) across three different (within-subject) conditions: (a) anodal stimulation (b) cathodal stimulation and (c) sham stimulation on the L DLPFC. In contrast to anodal stimulation, which I predict will replicate an improvement in motor performance, I predict that cathodal tDCS will lead to a relative decrease in reaction time from baseline. These conditions should be distinct from the sham condition, for which no reliable change from baseline is expected, save for any changes reflecting expectancy effects. The result revealed an unexpected reversed effect of Cathodal tDCS in RT which suggests that Cathodal tDCS may also have the ability to improve motor ability. Potential possibilities and limitations of this study were discussed.

The Effect of tDCS on Motor Skills

The history of using electricity as a brain stimulation can be traced back to Classical Antiquity. In 43 AD, ancient Greece, the physician Scribonius Largus used electric shocks from electric rays as a treatment to relieve patients' headaches. He states in *Hippocratic Oath*, 'To immediately remove and permanently cure a headache, however long-lasting and intolerable, a live black torpedo is put on the place which is in pain until the pain ceases and the part grows numb (Cannon, 2019)'. These types of treatments are not stable nor safe; people back in the ancient time were also not able to explain the mechanism behind it. It has long disappeared from medical treatments, and patients with headaches are most frequently treated with pharmaceuticals (Schaffer, 2006). However, the benefits brought by the treatment inspired the latter generation. Researchers believe that, through the current stimulation to the brain, it can not only heal the headache but also can enhance the ability of the brain such as cortical activity and neuroplasticity.

Brain Stimulation: A Rapidly Growing Field

Today, with developments in technology, electronic devices for head-zapping replaced the torpedo and researchers now have better, safer ways of testing how the application of electrical currents can alter the brain and the capacities it supports. In the last forty years, brain stimulation treatments and techniques have increased in neuroscience and clinical fields. Deep brain stimulation, the most invasive way of these techniques, allows the direct current stimulation into the deep structures of the brain, such as thalamic, subthalamic, and pallidal nuclei (Perlmutter & Mink, 2006). This technique has been used to treat dystonia in Parkinson's

disease and holds the potential for helping those with obsessive-compulsive disorder and mood disorders (Jakobs, Fomenko, Lozano, & Kiening 2019). These methods of stimulation are limited, however, by the need to surgically penetrate the skull, a costly endeavor with significant medical risks. Thus, more non-invasive technologies such as transcranial magnetic stimulation (TMS) and transcranial direct-current stimulation (tDCS) have emerged in recent years (Stilling, Monchi, Amoozegar & Debert, 2019).

Scientific and Clinical Uses of tDCS

tDCS, a form of neurostimulation, was originally developed as a treatment for psychiatric disorders such as depression, schizophrenia, and obsessive-compulsive disorder (Moffa, Brunoni, Nikolin, & Loo, 2018). Around twenty years ago, tDCS emerged as a safe, and relatively low-cost non-invasive brain stimulation (NIBS) technique, with research pointing to the potential for it to improve a range of behaviors including motor coordination, vigilance, and learning (Priori et al., 1998; Hannah, Iacovou, & Rothwell, 2018). For instance, researchers have utilized it to examine the effects of cortical modulation on language (Monti et al., 2013), decision-making (Soyata, Aksu & Woods, 2019), sensory perception (Vaseghi, Zoghi & Jaberzadeh, 2014), and memory (Vorobiova, Pozdniakov & Feurra, 2019). Also, tDCS has been proposed as a new tool for enhancing motor abilities such as playing pianos, gaining explosive strength for athletes, and training the reaction time for snipers. This is achieved by placing two electrodes--one positive (the anode) and one negative (the cathode) on the scalp, and running a current across them. It has been proven to be effective on stimulating the underlying brain regions by altering cortical excitability and neuroplasticity (Márquez-Ruiz et al., 2012).

The Effect of tDCS on Motor Evoked Potentials (MEPs)

Motor evoked potentials is an important measurement to see the changes of motor skills in a stimulation. The term ‘motor evoked potential’ (MEP) usually refers to the action potential elicited by noninvasive stimulation of the motor cortex through the scalp. MEPs were originally reported following electrical stimulation (high voltage: 1000/1500 V, and short duration: 50/100 ms, pulses) of the motor cortex (Abbruzzese, 2010). The MEPs were mostly used to detect the motor changes in studies that related to transcranial magnetic stimulation, since magnetic fields pass unattenuated through the skull and scalp, without nociceptive activation, and penetrate easily into the brain generating an electrical current that activates the neural tissue (see Figure 1 as an example of TMS stimulation and followed MEPs) (Komeilipoor, Pizzolato, Daffertshofer & Cesari, 2013).

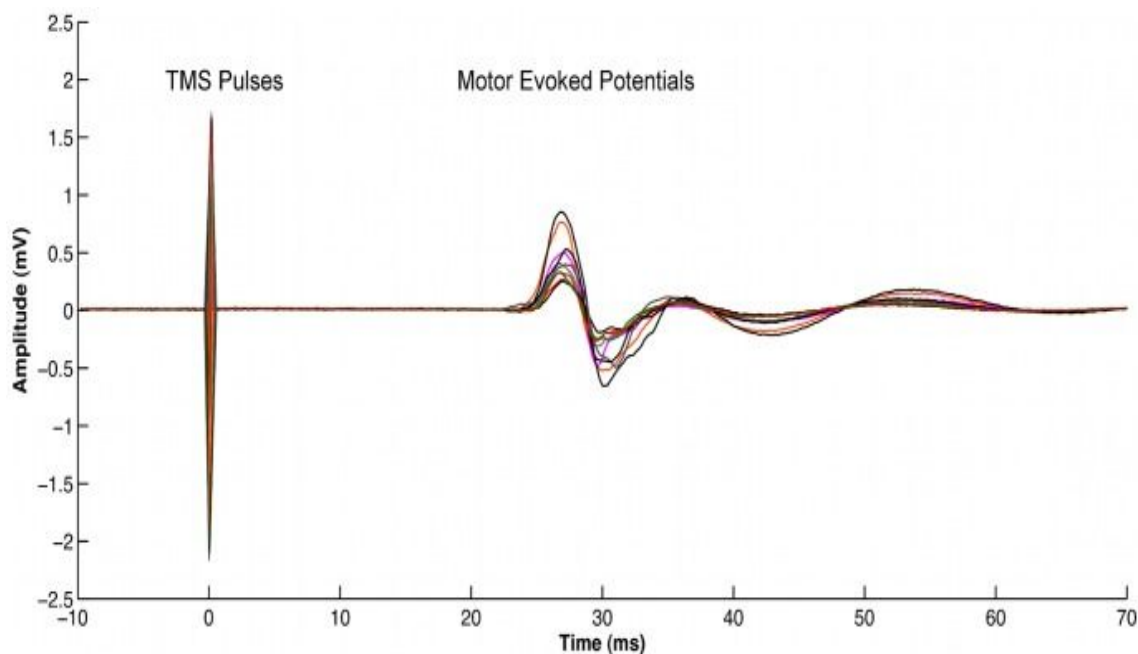


Figure 1 The vertical lines at 0 ms indicates when a single pulse of TMS was fired.

However, a study by Nuzum et al demonstrated that the tDCS can also enhance the frequency of the MEPs (2016). In their study, the anode electrode was placed over M1 while the cathode was placed over Fp2 with a 20 minutes long, and 2 mA current stimulation to see changes of reaction time in sequential finger tapping tasks of the right hand. The MEPs of the pre-test and post-test were recorded and the results showed that there is deeper vertex response in the MEPs of the right hand movements after the tDCS stimulation. This finding implies that the tDCS can improve the cortical excitability of a targeted brain region (Lauro et al., 2014) (see Figure 2 as an example of tDCS's effect on MEPs).

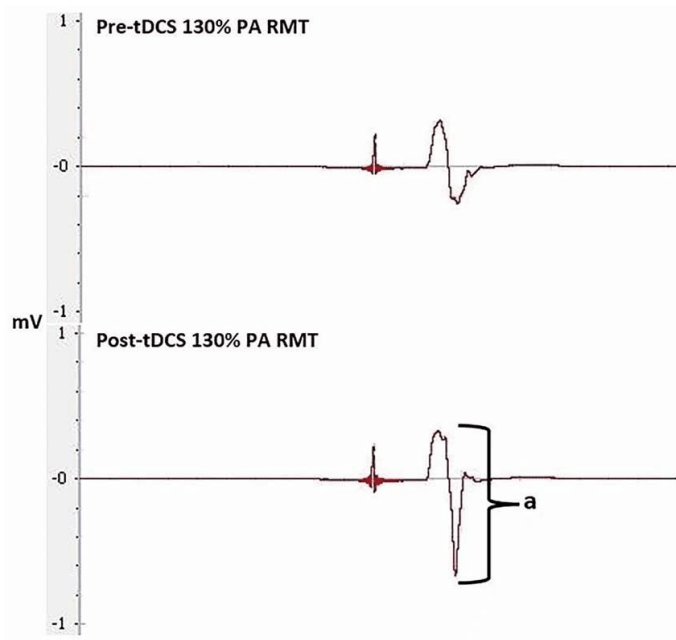


Figure 2 The MEPs records of Pre-tDCS and Post-tDCS from the study of Nuzum et al. Amplitude (a) was used to compare MEP size pre- and post-tDCS to determine tDCS effectiveness. In this figure, the post-tDCS MEPs have a higher frequency than the pre-tDCS MEPs.

Neurophysiology of tDCS: Cortical Excitability

Cortical excitability, the strength of the response of cortical neurons to a given stimulation that reflects neuron reactivity and response specificity, is a fundamental aspect of human brain function (Julien, et al., 2016). Nitsche and Paulus have shown that tDCS can be used for the control of cortical excitability (2000). In their study of relationship between the tDCS and cortical excitability, the tDCS stimulation to the scalp was correlated with increasing cortical excitability up to 40 percent immediately underneath both anode and cathode electrodes, whose effect lasts minutes to hours after the end of the stimulation. (Nitsche & Paulus, 2000). Electrophysiological studies have revealed that tDCS can change the cortical excitability of targeted areas immediately underneath the electrodes (Lang et al., 2005). Changes in cortical excitability rely on a variety of factors such as duration of stimulation and current density, with higher durations and greater current densities having greater and longer-lasting effects (Nitsche & Paulus, 2000) (See Table 1 for a summary of tDCS parameters and related effects). Similarly, fMRI and EEG studies reveal that although tDCS has its strongest effects on the underlying cortex, stimulation can provoke widespread and sustained changes in other brain regions as well (Kwon et al., 2008).

The example from Leonor et al. (2014) presented the effect of anodal tDCS on cortical excitability directly: With the anodal placed over the posterior parietal cortex and the cathodal over the contralateral supraorbital area, the red area in Figure 3 over the brain showed that the largest electric field area was underneath the anodal electrode (posterior parietal cortex), which means this area had higher cortical excitability than other areas.

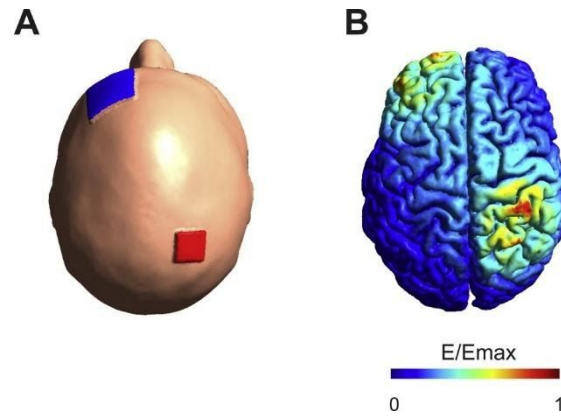


Figure 3. Model of the electric field during tDCS. A) Modeled montage including the anode (red) over the right PPC and the anode (blue) over the contralateral supraorbital area. With the anode placed over the posterior parietal cortex and the cathode over the contralateral supraorbital area, the cortical activity over the brain showed that the largest electric field area was underneath the anodal electrode (posterior parietal cortex). (Reproduced from Leonor, et al., 2014).

Table 1. Varying Parameters of tDCS

Parameter	Standard Range	Effect
Electrode Size	20 cm ² – 35 cm ²	Smaller electrode size results in greater final cortical current density, but also greater shunting to the scalp. Unipolar stimulation can be achieved through a small electrode by enlarging the area of the other electrode.
Current Intensity	1.0 mA – 2.0 mA	A current intensity of 0.6 mA is necessary to observe after-effects. Larger current intensity results in greater amplitude of effect (as measured by MEPs) and longer-lasting effects.
Current Density on Scalp Surface	24 μA/cm ² – 29 μA/cm ²	Larger current densities result in stronger effects of tDCS. Lower current densities (less than 24 μA/cm ²) for a few minutes do not induce any significant effects. (This is the ratio of current intensity and electrode size).
Stimulation Duration	5 min – 30 min	Longer duration results in longer-lasting effects. Whereas 5 to 7 minutes of tDCS results in after-effects lasting for no longer than 5 minutes, tDCS from 9 to 13 minutes results in after-effects lasting from 30 to 90 minutes, respectively.
Stimulation Polarity	Anodal or Cathodal (applied to cortical region of interest)	Effect depends strictly on the orientation of axons and dendrites in the induced electrical field. Generally, anodal tDCS increases the excitability of the underlying cortex by depolarizing neuronal membranes to subthreshold levels, while cathodal tDCS applied over the same area decreases it by hyperpolarizing neuronal membranes.
Stimulation Site	M1, V1, Somatosensory Cortex, Dorsolateral Prefrontal Cortex	Site-specific and differential effects on a gamut of cognitive, behavioral, psychosomatic, and electrophysiological tests. While the polarizing effects of tDCS are generally confined to the areas under the electrodes, the functional effects appear to perpetuate beyond the immediate site of stimulation. Anodal tDCS of the premotor cortex, for instance, increases the excitability of the ipsilateral motor cortex and inhibition of contralateral motor areas.

Note: (Table excerpted with permission from Reidler et al. 2011)

Neurophysiology of tDCS: Brain Plasticity

Brain plasticity (or neuroplasticity) describes the capacity to generate new or reorganize existing neural pathways. Neuroplasticity allows organisms to adapt (or learn) from experiences (Kania, Zieba & Wrońska-Fortuna, 2017). In certain cases, it also permits the transfer of computational responsibilities from one region of the brain to another--either due to normal development or recovery from a brain injury.

Much like a child learning to ride a bike, a stroke patient learning to regain use of his hand, or a musician practicing the piano, the skill gradually becomes more fluid and refined with repeated practice. This is owed to the symphony of neurons coding and transmitting information throughout the nervous system, becoming more harmonious as they increasingly act in unison without unnecessary or untuned noise. This reflects the neuropsychologist Hebb's concept of the brain's neuroplasticity, captured in the saying "cells that fire together, wire together. (Bernard, 2010)." In other words, when one repeatedly performs a task, the relevant set of neurons supporting its execution fire together, over time strengthening the connections between those cells--across synapses. Over time, these connections become hardy neural expressways that link various parts of the brain, and stimulating one neuron in the sequence is more likely to trigger the next one spontaneously, making many tasks easier (Bernard, 2010).

Generally, motor skills (like learning to play the piano) require a great deal of spaced practice in order to become an expert. However, tDCS as a tool can induce and speed up neuroplasticity and modulate cortical functioning by applying a low direct current over someone's scalp (Stagg & Nitsche, 2011). The previous study has demonstrated that anodal tDCS applied to mouse motor cortex in vitro induced NMDA receptor (NMDAR)-dependent

long-term potentiation (LTP; a lasting increase in signal transmission between neurons thought to support long-term memory) when the stimulus was given concomitantly with synaptic activation (Fritsch et al., 2010). For example, the primary motor cortex is where the afferent axonal synaptic input (see Figure 4) can be facilitated by anodal tDCS. This illustrates the effects of anodal tDCS on the synapses of pyramidal neurons in the primary motor cortex. Anodal tDCS hyperpolarizes the membrane of the axon terminal facing the anode (Bikson et al., 2004). Despite the hyperpolarization, there is greater neurotransmitter release which is caused by an increase in intracellular Ca^{2+} in response to anodal tDCS, whereas a decrease of Ca^{2+} leads to lower neurotransmitter release (Pelletier & Cicchetti, 2014).

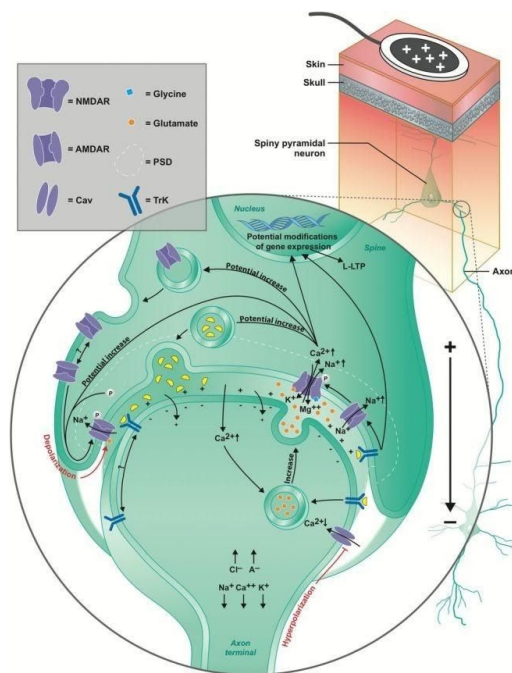


Figure 4. Putative molecular mechanisms of action of anodal transcranial direct current stimulation. Despite the hyperpolarization, there is greater neurotransmitter release, which is caused by an increase in intracellular Ca^{2+} in response to anodal tDCS, whereas a decrease of Ca^{2+} leads to lower neurotransmitter release (Reproduced from Pelletier & Cicchetti, 2014).

Electrophysiological studies have revealed that tDCS can change the cortical excitability of targeted areas immediately underneath the electrodes (Lang et al., 2005). The immediate effects of tDCS are due to the modulation at the subthreshold stage of neuronal membrane potentials, which increases or decreases the rate of potential firing activity. At the cellular level, the voltage gradient between the electrodes creates opposite polarities at either end of the neurons in the electrical field. This creates a difference in the transmembrane potential of the neuronal membranes and thus allows the current to flow across the membrane and through the neuron in accordance with membrane and intracellular resistance properties (Jefferys, Deans, Bikson & Fox, 2003). This current flow modulates the potential of the neuronal membrane and results in altered neuronal spontaneous activity.

Question & Theory

Does the cathodal direction of the current flow using transcranial direct-current stimulation (tDCS) affect one's ability to perform motor tasks? Based on previous research, motor skills can take weeks to months to acquire and can diminish over time in the absence of continued practice (Koneke et al., 2006). Thus, strategies that enhance skill acquisition or retention are of great scientific and practical interest (Janine et al., 2008). As mentioned above, anodal tDCS seems to have positive effects in different brain areas such as the posterior parietal cortex, primary motor cortex, and so on. Some studies have also explored the relationship between anodal tDCS stimulation and the left dorsolateral prefrontal cortex (L-DLPFC), which suggested that anodal tDCS has a positive influence on the motor and cognitive tasks such as pegboard task, finger tap tasking, the N-back task, and so on (Saruco & Rienzo et al. 2016).

However, the behavioral consequences of neuronal inhibition associated with cathodal stimulation are less understood or often seen as conflicted, though it has been known to temporarily impair performance (Roe et al., 2016). Systematic explorations of the behavioral consequences of neuronal inhibition associated with cathodal stimulation (i.e., reversing the polarity of the electrodes) remain relatively rare. Oftentimes, the cathode's placement on the scalp is a matter of convenience, rather than a topic of interest. Some researchers suggest that cathodal tDCS over a target region has the same behavioral consequences as anodal tDCS (Monti et al, 2008). Using one exception as an example, Christova, Rafolt, and Gallasch (2015) reported that cathodal stimulation over the primary motor cortex temporarily impaired motor performance in that reaction times to complete the task were increased significantly. It remains unknown whether the cathodal stimulation of the dorsolateral prefrontal cortex has the same effect.

To contribute to the ongoing debate over the influence of cathodal stimulation, as well as to the developing understanding of the dorsolateral prefrontal cortex's role in motor functioning, this thesis aims at testing whether cathodal tDCS over the left dorsolateral prefrontal cortex reverses the benefits seen in anodal stimulation of this region, in comparison to a controlled condition without sustained effects.

Specifically, I predict that the cathodal tDCS stimulation group will exhibit significantly slower reaction time and accuracy on FTT than participants in anodal condition. I also hypothesize that the cathodal condition will have significantly lower performance than participants in sham (control) condition.

Method

Experimental Design

I performed a single-blinded, randomized, placebo-controlled trial with a within-subject design to investigate the effects of tDCS on motor skills in healthy human subjects. The protocol for the investigation was approved by Bard College's Institutional Review Board (see Appendix I). Prior to participation, the subjects provided written, informed consent (see Appendix D).

Assessments: Finger-Tapping Task

The finger-tapping task is a motor learning task where participants were asked to tap the keys with their fingers while seeing stimulation on the computer screen. The task was conducted on participants' both hands, using their index, middle, ring, and pinky fingers, to tap the right keys following stimulation on the screen (Cellini, 2016). For this study, the reaction time (RT) and the accuracy (ACC) of participants' performances were collected to compare the changes before and after the tDCS stimulations. Since I wanted to focus on the direct changes of the finger's RT and ACC, there were no sequential tapping orders and all the key combos were randomized (Cellini, 2016) to minimize the working memory workload (Holm, Karampela, Ullén & Madison, 2017). This assessment took place immediately before and after the 10-minute active or sham tDCS sessions. The program was conducted on Inquisit 5 and code was adapted from the Millisecond Test Library. In the three periods, participants did the task on each hand for five minutes. The program was set up for participants to relax their hands for 15 seconds after 40 trials. Then the task started again until the 5 minutes elapsed. After participants finished the program with their dominant hand (right hand), then switched to another hand. In the right hand task, the program asked participants to put their right index, middle, ring, and pinky fingers on

the keyboard 'M', ',', '.', and '/'. Once they were ready, they were asked to press space to start, the screen showed four boxes and each one corresponded to one key. The screen lit up one box in red each time, the participants were asked to click the right keys as soon as possible and at the same time keep the accuracy. Once they click the right key, the screen automatically switches to the next trial. The left hand task had the same procedure. The only difference is to put their left index, middle, ring, and pinky fingers on 'Z', 'X', 'C', 'V'. (See Figure 5 as an example of the FTT process).

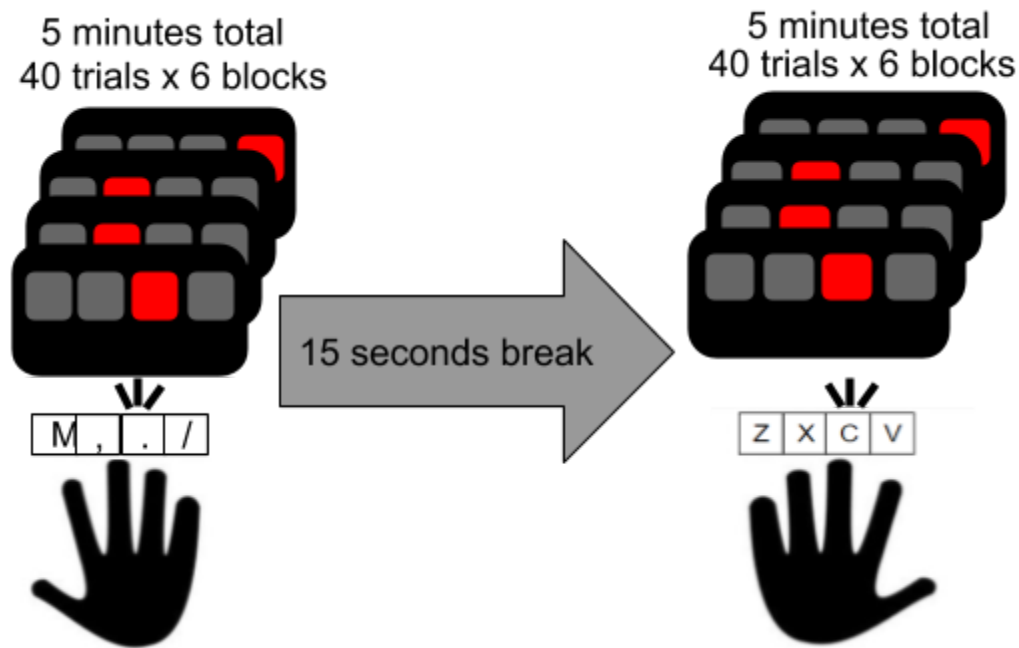


Figure 5 This is a FTT example of my study that participants started with their dominant hand, after finishing the five minutes tasks, they rested for 15 seconds and then switched to another hand to finish the task.

Participants

Based on a power analysis assuming alpha of 5% and beta of 20% (power = 80%), I determined to recruit (twenty-four) subjects between the ages of 18 and 30 (inclusive) from the Bard College area using online advertisements and flyers. However, due to the COVID-19 outbreaks in the U.S, I only recruited 10 participants at the end (see Table 2 for the statistical information of the participants). Criteria for exclusion was based on Thair et al (2017)'s standard criteria which included the following: chronic pain symptoms in the past six months, history of psychiatric or neurological disorders, substance abuse history in the past six months, history of adverse reaction to tDCS, current treatment for seizures and neurosurgery involving the brain. Participants who have a surgically implanted pacemaker and any metal embedded in the head were excluded (see Appendix B). Additionally, they had a normal/corrected-to-normal color vision. Participants were always asked to be willing to have felt tDCS sponges moistened with a saline solution (to allow for electrical conduction) introduced on their hair and scalp while sitting relatively still and performing the simple motor task described below. A standard screening questionnaire was used to determine eligibility prior to the study (see Appendix x).

Table 2. Information of Participants

Gender	%	N	Total
Male		2	10
Female		8	
Age			
18-21		3	10
22-25		5	
26-29		2	
Race & Ethnic			
American Indian		0	10
Asian		9	
Black		0	
Native Hawaiian		0	
White		0	
Latino		1	

Table 2 The information of recruited participants in this study.

Counterbalance

Counterbalancing is a technique used to deal with order effects when using a repeated measures design. In this study, the order effect may happen in the tDCS conditions (e.g. All participants start with the same stimulation condition). With counterbalancing, the participant sample was planned to divide in six, with each cell containing four participants. All participants were randomly assigned to each group. These six groups are presented in Figure 6 below.

Counterbalanced group	
ACS (4)	ASC(4)
CAS (4)	CSA(4)
SAC(4)	SCA(4)

Figure 6 The counterbalanced six groups. Each letter represents the stimulation condition (A: Anode; C: Cathode; S: Sham) The order of the letter means which condition started first, second and the last. For example, if a participant was in an ACS group, then he/she received the Anodal stimulation in the first visit, the Cathodal stimulation in the second visit and the sham stimulation in the last visit.

Procedure

In addition to undergoing the online screening, participants were invited to Preston Hall for a total of three laboratory visits. The three visits (each lasting approximately 25-30 minutes) were scheduled either 24 or 48 hours apart from each other, depending on participant/researcher availability in order to account for potential time-of-day effects. Due to scheduling conflicts, four participants were unable to return at the exact same time of day to do the following session, their visits instead ranged from 5-8 hours from the first time they visited. During the first visit, participants were asked again to the same screening questionnaire in order to confirm their eligibility. Provided they were deemed eligible, they were then invited to read and sign the consent form. Aside from the consent process during the first visit and the debriefing process in the third visit, the three visits were structured similarly from the perspective of the participants.

Prior to any data collection, participants were fitted with a specialized swimming cap marked with the International 10-20 system defining electrode placements for the purposes of electrical recording (Shields, Morse, Applebaugh, Muntz & Nichols, 2016). A wax pencil was used to mark the locations of the F3 and F4 electrode placements on the left and right side of the front part of the scalp, respectively. The reason why these two areas were chosen is that prior research demonstrated that they are the most involved brain regions of the motor learning process (see Figure 7 for an example of 12-20 channel EEG map and the locations of F3 and F4 areas) (Velasques et al., 2007). Despite not having a structural image of participants' brains with

which to align the electrode placement, these electrode sites are known to sit above the dorsolateral prefrontal cortex for most individuals (Rich & Gillick, 2019). No electrodes were placed before participants finished the Pre-tDCS finger-tapping task.

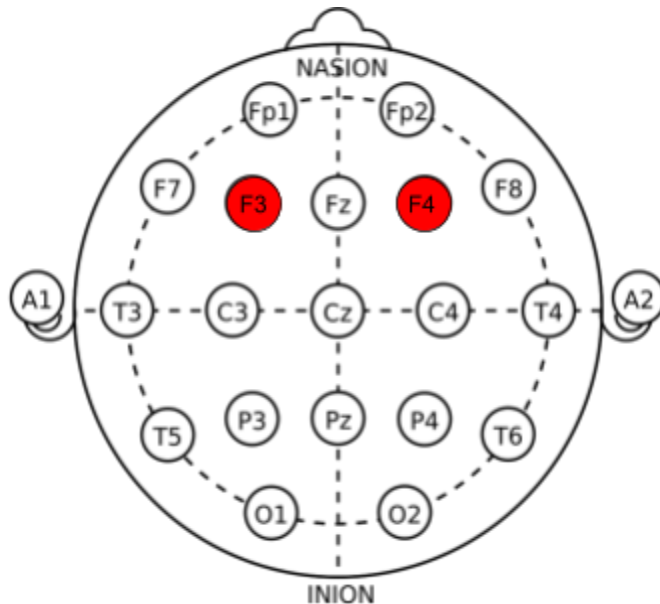


Figure 7 An example of 10-20 channels EEG map. The F3 and F4 regions are marked in red color.

Specifically, each visit could be subdivided into three phases: Pre-tDCS, tDCS, and Post-tDCS. During each of these three phases, the participant was asked to complete 10 minutes of the Finger Tapping Task (FTT) described below. Stimulation (either anodal, cathodal, or sham) was applied only during the central tDCS phase. The order of the three stimulation conditions was counterbalanced across participants. The proposed design allowed me to evaluate the effects of anodal, cathodal, and sham tDCS for each subject (i.e., within-participant, see Figure 8 for an overview of the experimental procedure).

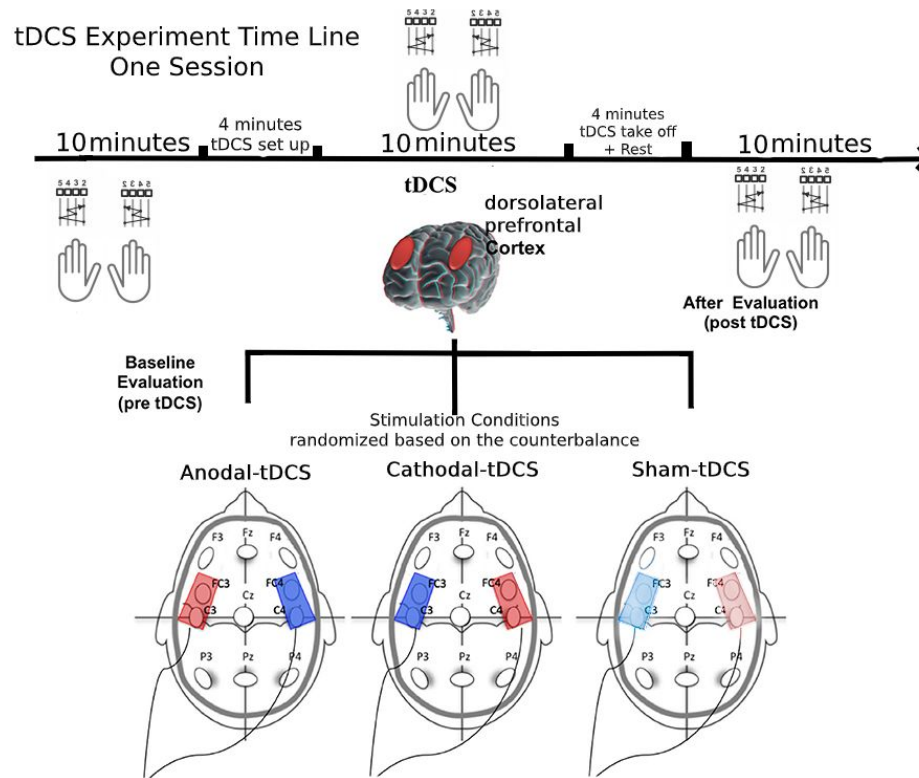


Figure 8. One Session of the tDCS study timeline. Participants were randomly assigned to one condition each time based on the counterbalancing.

At the beginning of each task, participants were asked to complete the Finger Tapping Task. Then they were fitted with a swimming cap with markers used to identify the rough location of underlying brain regions of interest. Then, two electrodes were placed over the participant's scalp on top of conductive sponges (moistened in a saline solution) at locations roughly above the left and right dorsolateral prefrontal cortex (F3 & F4). The electrodes and sponges were secured with a headband. Participants were then asked to complete the FTT again. After participants completed the during-tDCS part, the electrodes were taken off and participants were asked to finish the FTT. After the participants finished each session, they received the post-questionnaires asking about whether they were feeling any side-effects (the tDCS Post

Experiment Questionnaire, See Appendix F). After the participants completed three sessions, I verbally informed them of a debriefing statement and gave them a paper version of it as well. After all was completed, I answered any questions they may have had and paid them \$7 for participating using Venmo.

Transcranial Direct Current Stimulation

I administered direct current (DC) to the scalp using rubber electrodes enclosed in saline-soaked sponges (35 cm²). Rubber bands were used to hold the electrodes in place on the scalp and the electrodes were connected by wires to a battery-powered DC generator called Brain Driver company's tDCS Device V2.1 (Figure 9). This commercially available device allows the operator to establish the current strength and stimulation duration. It is powered by a 9-volt battery, limiting any risk. The anode electrode was positioned on the scalp just above the left dorsolateral prefrontal cortex (F3) and the cathode was placed on the right forehead above the right Dorsolateral Prefrontal Cortex (F4). According to a previous study by Fregni et al. (2006), this montage seems to bring the optimal result in improving finger movement and cortical excitability in F3.



Figure 9 The tDCS Device V2.1 which includes anodal and cathodal tDCS electrodes, 9-volt battery and headband to stabilize the electrodes over the head.

During active stimulation conditions, I administered 1 mA of active tDCS to F3 or F4 areas (based on the conditions) for 10 minutes. During sham stimulation conditions, identical protocols were used, but tDCS current was only administered for the first 30 seconds of the 10-minute session. Previous literature has demonstrated that application of current for 30 seconds is a valid method of blinding and that application of current for under 3 minutes does not influence cortical excitability (Miranda, Lomarev & Hallett, 2006; Gandiga, Hummel, Cohen, 2006). Participants received active and sham stimulation typically feel an itching sensation on the scalp beneath each electrode at the start of stimulation that wanes over time. Of note, studies have shown that a single session of active tDCS using 1 mA current is safe in non-pregnant, healthy adults, with only minor and short-lasting adverse effects (Iyer et al. 2005). Sponges were retained for a particular participant's use across the three visits (sanitized after each visit and stored in a sealed Ziploc bag). Different sets of sponges were used for each participant. The swimming cap was sanitized after each visit, following standard lab procedures.

Statistical Analysis

I analyzed data by using the SPSS. I ran a Mixed-design ANOVA in which the dependent variables were the change of the RT and ACC in the FTT. The two within-subject independent variables are Conditions (Anodal, Cathodal & Sham tDCS) and Timepoint (Pre-test & Post-test). The between subject variable is the counterbalance. I set the alpha (significance) level at 0.05.

Results

Due to the COVID-19 outbreak in the U.S., data collection was halted prior to reaching the pre-established sample size. Data collection from 11 participants was completed on March 20, 2020. Of these participants, one (the first one run) was excluded from all analyses due to a programming error in the FFT that was corrected for the rest of the participants. It occurred that the program did not run the full ten minutes during the tDCS stimulation period. Based on the exclusion criteria by Moliadze et al. (2015), all the participants should receive a minimum of 10-minute stimulation to see the change of the behavior between pre-test and post-test. This participant was excluded from the final analysis. The problem with the program was fixed after the first participant and there were no other problems with the program and exclusion came out.

Reaction Time (RT) Trimming

Prior to analysis, it is common practice to trim the reaction time data, removing what could be considered overly slow or fast responses that likely reflect unintended distractions or mistaken button presses, rather than condition-specific task-related performance. While there are a number of standards for doing so, rather than adopting an arbitrary cutoff for high and low reaction times that is applied across participants, I adopted a flexible approach that allows for participant-specific cut-offs based on the number of standard deviations (plus or minus 2.5) away from their mean reaction time in each condition based on the average score of the participants. This “participant standard deviation” cut-off is considered more appropriate, especially when dealing with small samples (Grange, 2014). The Inquisit 5 code was programmed to calculate the “after trimmed” average automatically after each condition was done.

Data Transformations

Confirming expectations due to the nature of the measures, visual inspection of the trimmed RT and raw ACC data (ignoring stimulation condition and counterbalancing order) were highly skewed in the positive and negative directions, respectively. Overall, The RT data clustered around 0 ($M = 349.82$; $SD = 38.43$), whereas ACC data clustered near ceiling-level performance ($M = 0.97$; $SD = 0.02$). These intuitions were confirmed by analyses for skewness and kurtosis that RT data is left skewed which the skewness statistic is 0.22 and kurtosis is -1.14, whereas the ACC data is right skewed which the skewness statistic is -0.425 and kurtosis is -1.25. Though I intended to focus on RT due to the expectation that ACC would be high, I also planned on running parametric statistics, including ANOVAs and t-tests, on the ACC data in order to determine whether the RT effects were consistent with the ACC effects or if there was a speed-accuracy trade-off. Given these tests' assumption of normality for the dependent variables (Sharma, 2019), I conducted a Shapiro-Wilk test separately for these measures, which indicated significant deviations from normality (RT: $p = 0.012$; ACC: $p = 0.02$). While one option was to choose a non-parametric approach to data analysis, another is to transform the data to better meet the assumption of normality. One common practice for transforming positively skewed reaction time data is the log transform (Teekens & Koerts, 1972)--a technique that has regularly been applied to motor performance reaction times, specifically (Lo & Andrew, 2015). The arcsine transformation, in contrast, traditionally has been applied to proportions (ranging from 0-1) that are negatively skewed, like ACC here. Graphical representations of examples of the normalization effects of the transformations are presented in Figure 10. Confirming the benefit of these transformations on this dimension, the Shapiro-Wilk tests revealed that both RT ($p = 0.15$)

and ACC ($p = 0.48$) data is now normally distributed. Unless otherwise specified, the inferential statistical tests described below were conducted on the transformed data. Comparisons to analysis on the raw (trimmed) data are presented when appropriate.

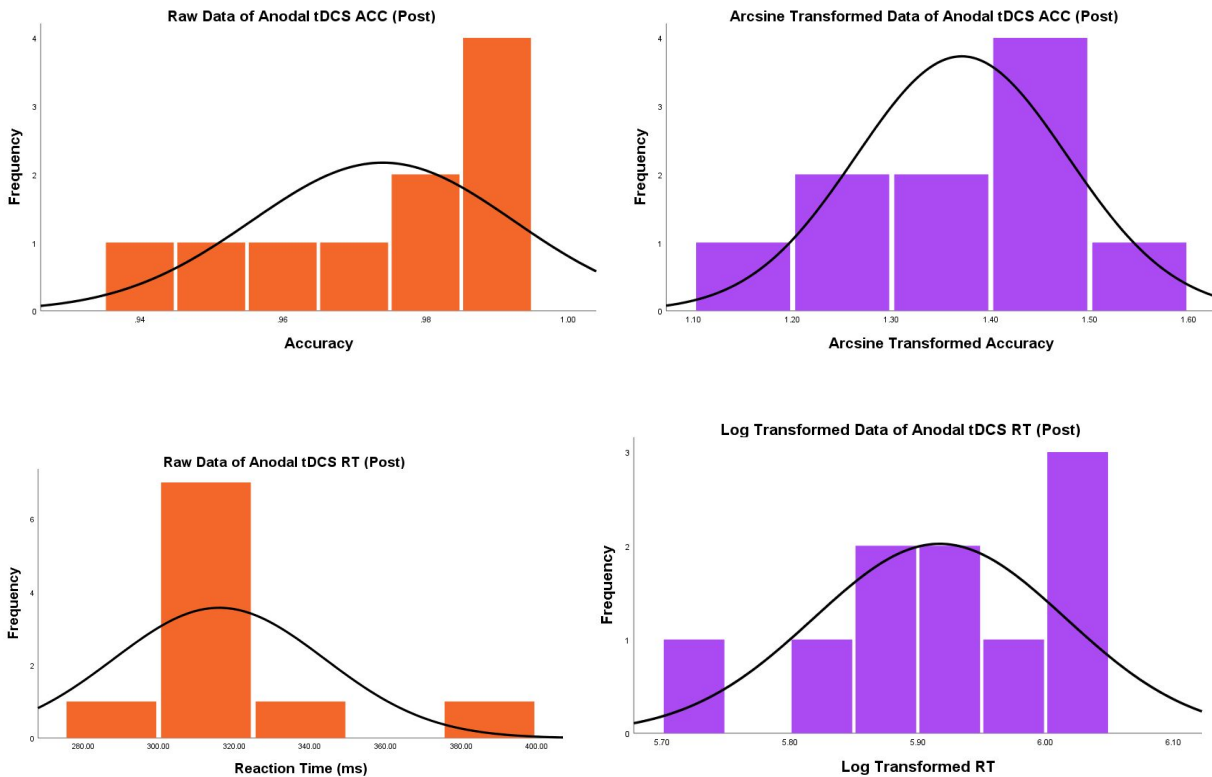


Figure 10 The comparison between the raw data distribution and transformed distribution of Anodal tDCS's post-test RT and ACC in histograms as an example. The raw data is presented in orange and the transformed data is in purple. It is clear to see that the skewed data is normally distributed after the transformation. Data in different conditions all showed the same change.

Counterbalancing

As originally designed, there were six counterbalancing orders that captured the order in which participants experienced the stimulation conditions: anodal, cathodal, and sham. Even as initially envisioned, this study--which could be considered a pilot--was going to be underpowered, due to the expected difficulties in recruiting and scheduling participants. Given

the original plan, four participants were supposed to have experienced each counterbalancing of the six counterbalancing orders. Due to the Covid situation curtailing data collection, full counterbalancing was not achieved and the cell size was even more restricted. In order to account for the expected differences in counterbalancing orders, I still wanted to include some version of this factor in my statistical model. To make this work, I decided to reimagine the counterbalancing fact by focusing on the influence of the first stimulation condition, collapsing across the order of the two conditions that followed. This would yield three reduced counterbalancing conditions: anodal-first, cathodal-first, and sham-first. These groups (see Figure 11) prioritized the first stimulation condition. In their first session, participants had no comparison to the other stimulation conditions; therefore, they represent what could be, perhaps, the cleanest estimate of the effect of that stimulation condition--devoid of carry-over effects. For instance, a participant who experienced the sham condition first would, presumably, be less able to tell that they were in the sham condition, compared to another participant who experienced full anodal (or cathodal) stimulation first.

Planned Counterbalance		Changed Counterbalance
N= 24		N = 10
ACS (4)	ASC (4)	ACS+ASC (3)
CAS (4)	CSA (4)	CAS+CSA (4)
SAC (4)	SCA (4)	SAC+SCA (3)

Figure 11 The comparison between the planned and changed counterbalancing definitions. Since the original plan was to run 24 participants, there were six counterbalancing conditions and each

contained four participants. The final dataset only included 10 participants, however. To avoid even smaller group sizes in each cell, the counterbalancing plan changed to only consider which condition starts the first time and ignore the order for the rest of the session.

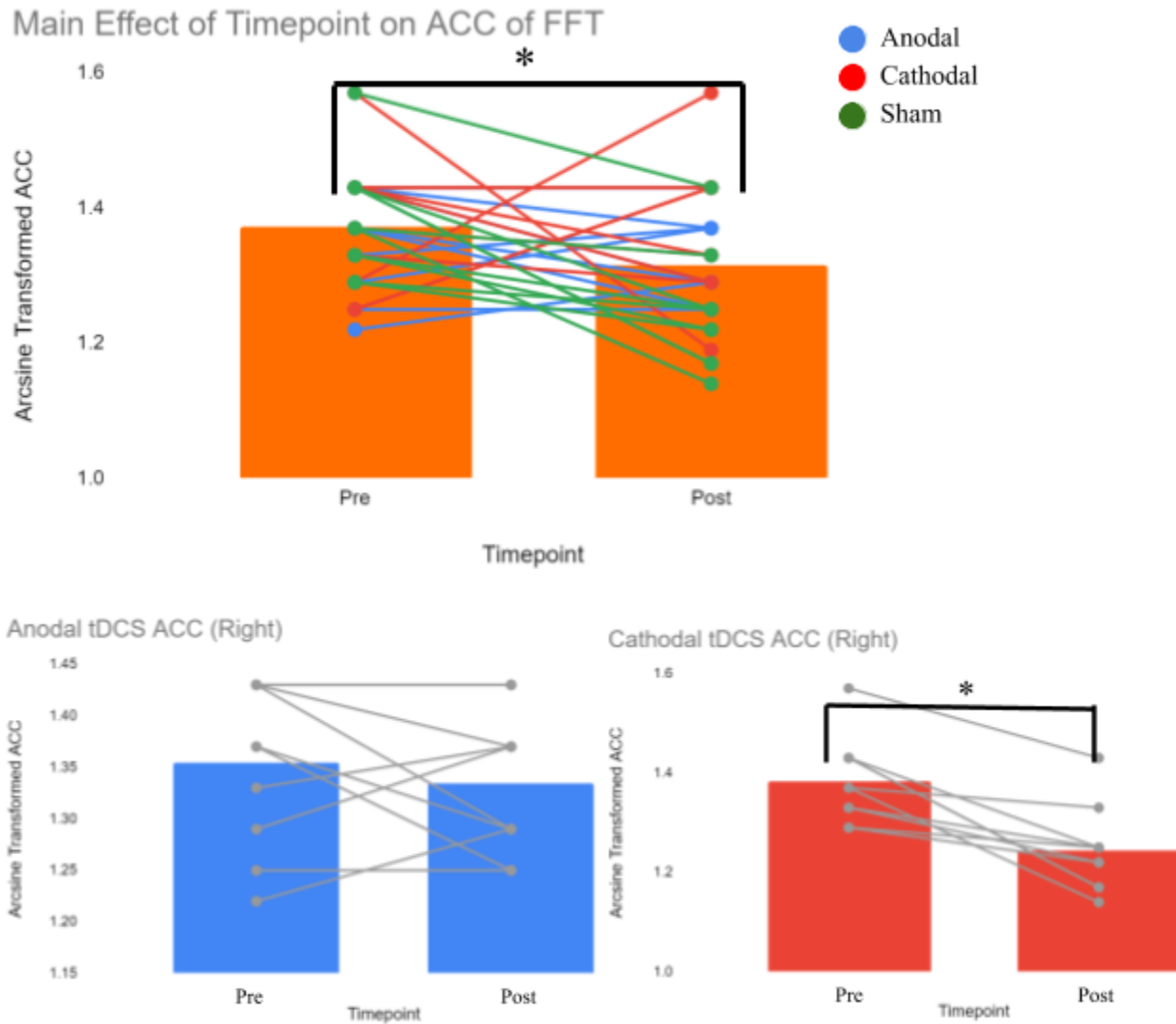
Statistical Model

After (trimming, for RT only) and transforming my dependent measures, I conducted two mixed ANOVAs--one on RT and the other on ACC data for right-hand performance. The tDCS Stimulation Conditions (anodal, cathodal, and sham) and Timepoint (Pre- vs Post-stimulation) as two within-subjects factors and the reduced Counterbalancing order (anodal-first, cathodal-first, or sham-first) as a between-subject factor. After running and presenting the results of the omnibus ANOVAs, I examined specific contrasts using paired t-tests (two-tailed). An alpha level of 0.05 was adopted for all analyses.

Accuracy (ACC)

In ACC, there was a main effect of Timepoint ($F(1,29) = 3.356, p = 0.03$) which reveals that the Post-test has a lower ACC rate ($M = 1.32, SD = 0.10$) than the Pre-test ACC rate ($M = 1.37, SD = 0.09$). Also, there is an interaction between Timepoint and Conditions ($F(1,7) = 5.677, p = 0.049$). This suggests that there is a difference among the three conditions with the Pre and Post test. To see the Timepoint differences in each Conditions, a one-way ANOVA was conducted and there is a significant difference in Cathodal ACC ($F(1,19) = 9.310, p = 0.007$), which revealed that there is a big rate drop-down in this condition between Pre-test ($M = 1.38, SD = 0.08$) and Post-test ($M = 1.24, SD = 0.08$). No significant results were found in both Anodal ($F(1, 19) = 0.40, p = 0.53$) and Sham conditions ($F(1,19) = 0.02, p = 0.90$). (see Figure 12 for the main effect of Timepoint and the interaction between Timepoint and Conditions)

There is no significant difference found in the interaction between Timepoint and Counterbalance ($F(1,7) = 2.796, p = 0.128$) and interaction among three factors ($F(1,7) = 7.313, p = 0.716$).



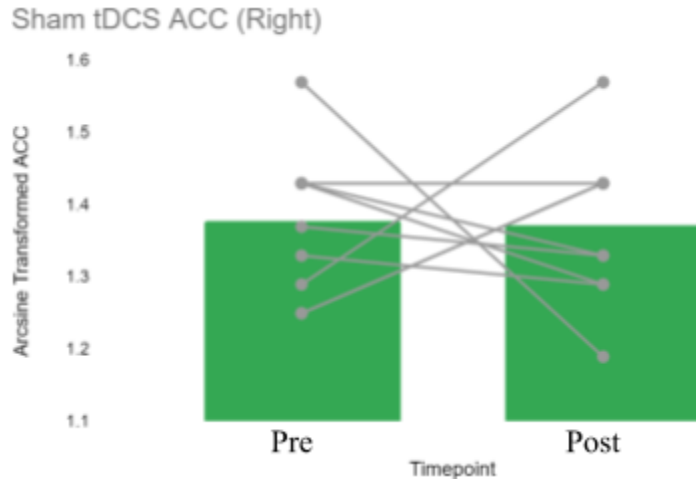


Figure 12 : The first figure presents the main effect of Timepoint. All participants' results in three conditions are presented in three colors, Blue-Anodal, Red-Cathodal & Sham-Green. The orange bar shows the average of the sum of the three conditions in both Pre-test and Post test. 2) The rest three figures show the Timepoint differences in each condition. The results of each participant are shown by the grey line. All of the ACC are presented in Arcsine Transformed data.)

Reaction Time (RT)

In terms of RT, I found a main effect of Timepoint (Pre & Post) ($F(1,7) = 65.20$, $p < 0.05$), with the reaction time on the Pre-test being slower ($M = 5.87$; $SD = 0.098$), on average than reaction times on the post ($M = 5.83$; $SD = 0.098$) (see Figure 13). This effect was qualified by a significant interaction between Condition and Timepoint ($F(1,7) = 37.75$. $P < 0.05$).

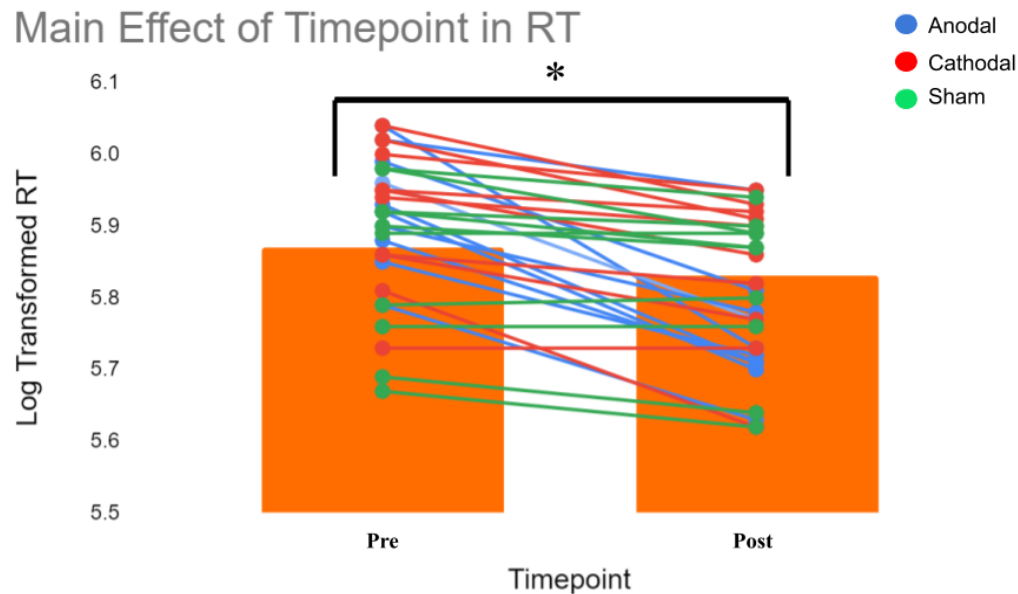


Figure 13 The main effect of the timepoint in RT is presented in this figure. Different color lines show all participants' RT in three conditions of pre-test and post-test.

To see the changes in different conditions before and after the stimulation, a one-way ANOVA test was run to compare Pre and Post test scores in the three conditions. Based on the existing evidence in the literature, I predicted significant improvements in Anodal and Sham tDCS which the RT should be faster in Post-test than in the Pre-test, even without the stimulation (Sham tDCS)(Meinzer, Lindenberg, Antonenko, Flaisch & Flöel, 2013). By inspecting the graph, it can be seen that all three conditions showed improvements in RT (see Figure 14). However, the test showed that there is no effect of Anodal tDCS ($F(1,19) = 0.091, p = 0.766$) and sham tDCS ($F(1,19) = 0.003, p = 0.642$) between Pre-test and Post-test of the RT score which means there is no change of RT in both Anodal and Sham condition. Based on prior studies, the anodal condition is supposed to have the highest chance to have a significantly decreased score (The RT in Post-test is significantly faster than in Pre-test) since it improves brain activities (Meinzer et al., 2013). Besides, the Cathodal condition showed a significant effect of Timepoint ($F(1,19) =$

0.049, $p = 0.042$) that the Post-test RT ($M = 5.91$, $SD = 0.1$) is faster than the Pre-test RT ($M = 5.84$, $SD = 0.10$). This suggests that the Cathodal tDCS improves the RT of FTT after 10 minutes of stimulation (Jeffery, Norton & Roy et al. 2007).

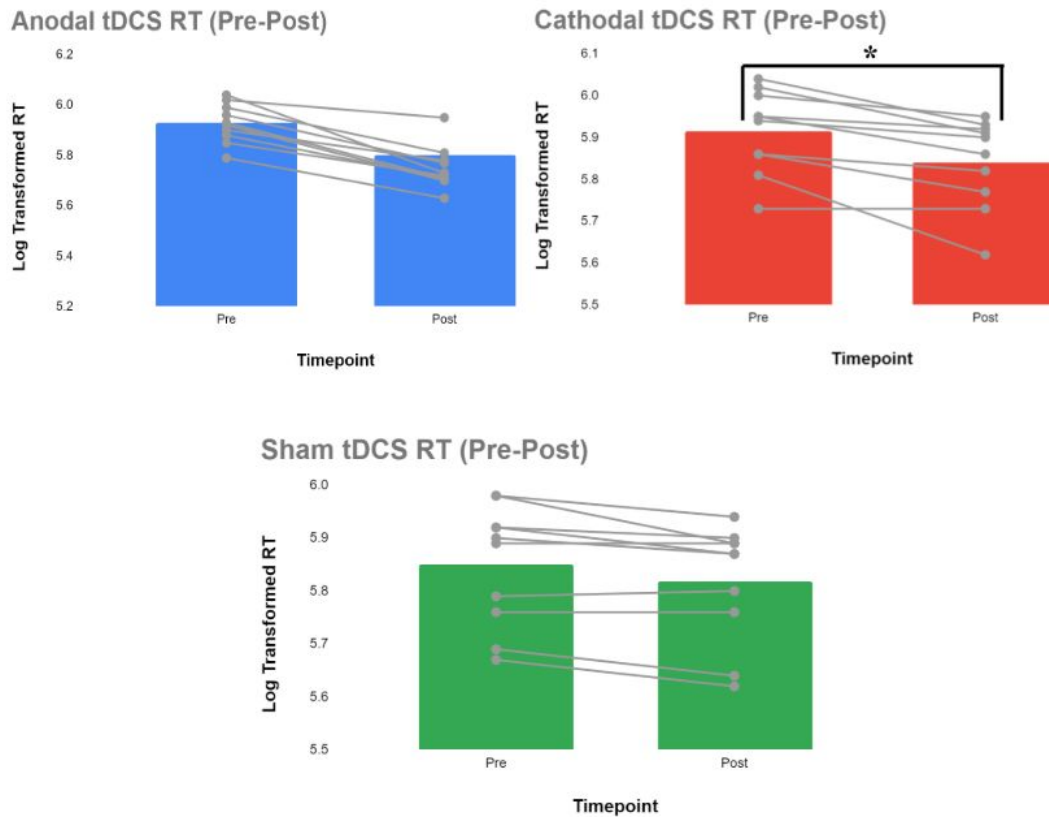


Figure 14. The reaction time of the FTT for all participants in three Conditions. Each point connected from Pre-test to Post-test represents an individual participant's RT score changes from the Pre to Post test.

However, there is a potential interpretational issue that needs to be considered. First, participants may intentionally or unintentionally shift their focus from performance speed (RT) to accurate performance, or vice versa. This speed-accuracy trade-off has been discussed at length elsewhere, including in the motor domain and may arise due to instructional manipulations, fatigue, or brain stimulation (Lammert et al., 2018). In this experiment, I

instructed participants to complete the trials as quickly as possible, without sacrificing accuracy. However, there is no guarantee that participants could or would be able to follow this for the entirety of the experiment. They may still focus on the response speed and ignore accuracy which leads to a RT-ACC trade-off. To see if there is an RT-ACC trade-off, the comparison of the improvement of RT and ACC was made by subtracting the pre-test score from the post-test in both RT and ACC (RT Post-Pre ; ACC Post- Pre). As it turns out, there are few subjects (Participant 1, 8 & 9) that have the improvement of RT with the drop-down of ACC (see Figure 15).

An ANCOVA test was run to test if the ACC as a covariate had any effect on RT. The result presented that ACC has no effect on RT ($F(1,19) = 0.029, p = 0.11$) which suggests that the RT-ACC trade-off did not found in this study. The RT significant result was still found in Cathodal condition ($F(1, 19) = 23.295, p < 0.05$).

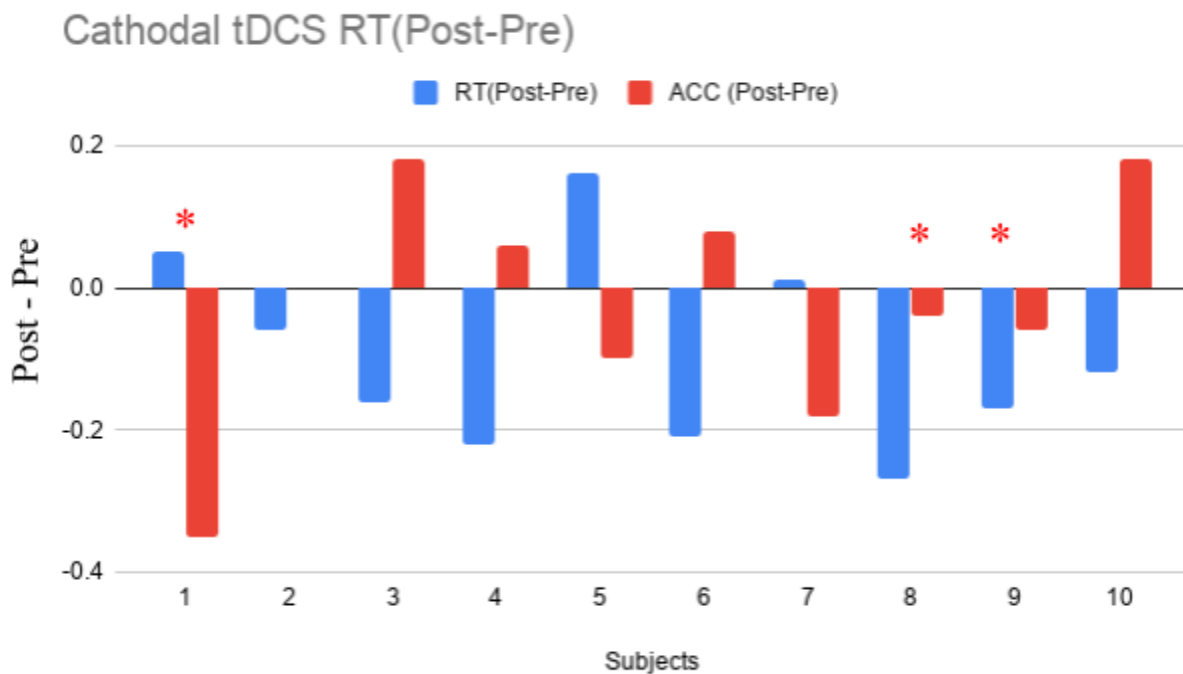


Figure 15 The comparison of the improvement in Cathodal tDCS by subtracting the pre-test score from post-test in both RT and ACC. The score above zero means a slow down in RT and a decrease in ACC. The score below zero means improvements in both RT and ACC. The three outliers were marked as a red star above them.

To see the Post-test differences between conditions, the ANOVA is needed. However, the time of running the three sessions for participants may vary (e.g., one participant came for anodal tDCS in the afternoon and Cathodal tDCS in the evening). To see if there is a ‘time of the day’ effect, a ANOVA test was run and it showed that there is no significant difference ($F(1,29) = 1.862, p = 0.175$) among the three conditions’ pre-test, suggesting that there the time of the day has no effect on the study. This means the baseline score of each participant was similar. Because of that, the comparison in the post-test can be conducted. The one-way ANOVA showed that there is no significant difference among the three conditions in the post-test group ($F(2,29) = 2.088, p = 0.143$), which suggests that the Cathodal tDCS has the same effect as the other two conditions.

Moreover, prior research pointed out that to see the small changes in the pre-test and post-test, the averaged-based approach (above shown) is not the only gold standard way. The individual-based approach can detect smaller changes (Estrada, Ferrer & Pardo, 2019). To apply this approach to my analysis, the (post-test) minus (pre-test), in the single group pre-post design and calculated based on the standard deviation after the subtracting. With the individual-based approach, the differences for cathodal tDCS with Anodal and Sham condition were significant (Anodal: $F(1,19) = 13.138, p = 0.02$; Sham: $F(1,19) = 5.805, p=0.027$). Suggesting that the Cathodal tDCS does have an impaired effect on participants shows that the RT of the task is longer than the other two groups.

There is also an interaction among the three factors ($F(1, 7) = 1.438, p = 0.02$) which means that when the order of the test changed, the conditions score of pre-test and post-test was changed. (See Figure 15 of the interaction among three counterbalancing conditions)

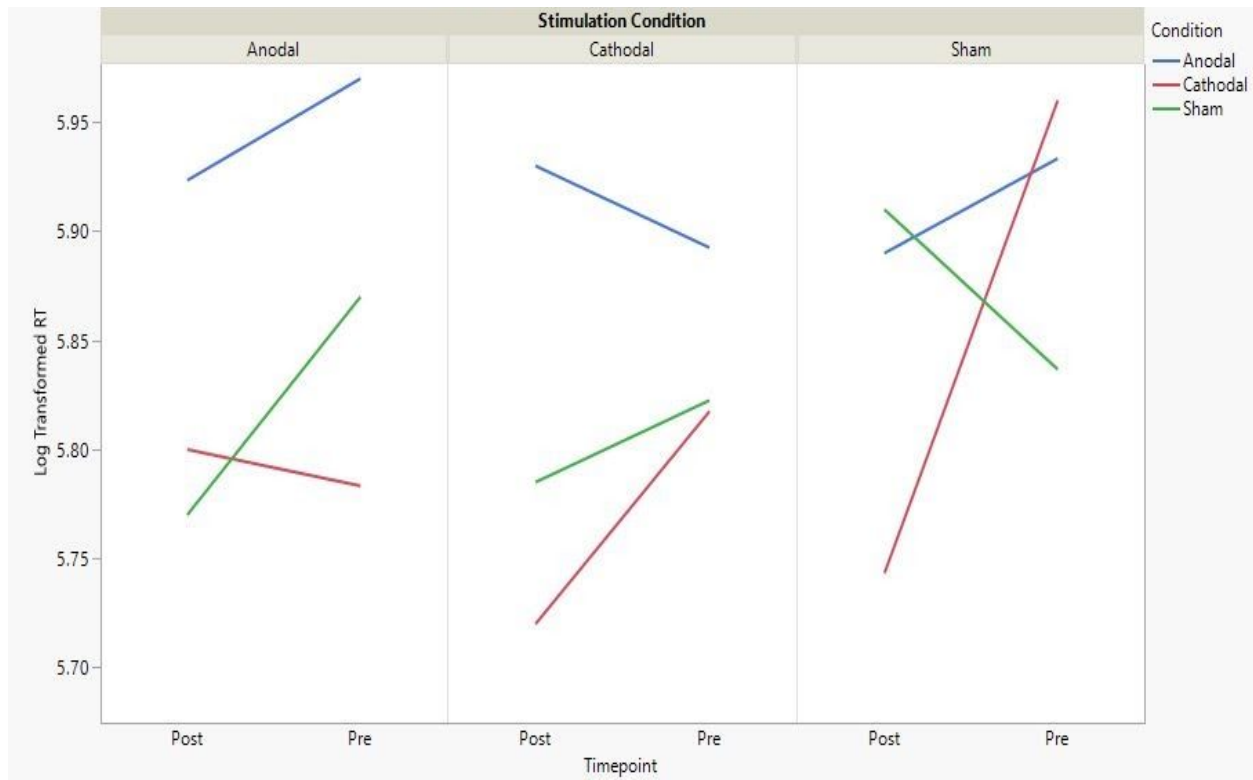


Figure 15 The interaction among the three factors of RT are presented in this figure. The Stimulation Condition is the Counterbalance of the study that starts first of the study. Each line is the average score of participants in three different conditions.

This interaction suggests that when the order of the study starts with the Sham tDCS, RT of the Cathodal tDCS decreases significantly. This suggests that the counterbalance may affect the behavior and during the test. However, since the sample size is too small, I can not tell if this is a reliable result. More limitations and possibilities answering why I got these results will be discussed in the following part.

Discussion

Running a small, externally generated current through the brain has been shown previously to affect a wide range of behaviors, including motor performance. Though much remains unexplored, numerous factors appear to influence the strength and direction of these influences, including the voltage, the surface area of the stimulated region, the duration of stimulation, and the brain regions targeted. This Senior Project was intended to clarify an outstanding question in the tDCS literature as to whether the polarity of stimulation targeting the left dorsolateral prefrontal cortex affects the right (dominant) hand's performance on a finger-tapping task (FTT). Paralleling the results of the sham condition, 10 minutes of anodal stimulation at 1.0 mA (i.e., with the anode placed on the scalp roughly over the left dorsolateral prefrontal cortex and the cathode placed over what is likely to be the right dorsolateral prefrontal cortex) altered neither reaction time nor accuracy on a final test relative to baseline. Yet, left reversing the polarity, such that the cathode was placed over the left dorsolateral prefrontal cortex resulted in a significant improvement in reaction time. While I had predicted the null effect in the sham condition, the latter two findings stood in stark contrast to my original predictions. First, numerous data points in the existing literature have demonstrated a facilitatory effect on right-handed motor performance speed after applying anodal stimulation to the left dorsolateral prefrontal cortex (e.g., Keitel, Øfsteng, Krause & Pollok, 2018). Yet, the reaction-time difference between pre-test and post-test in condition--which itself was not reliable--was statistically indistinguishable from the sham (control) condition. Second, despite having predicted a reaction-time effect of cathodal stimulation of the same target region, the observed effect--while reliable in my small sample--was in the opposite direction as had been

predicted. Participants were actually faster on the post-test, compared to the pre-test, even after statistically controlling for the non-significant differences in accuracy across time points. The results of this experiment suggest that 10 minutes of Anodal or Sham tDCS targeting the left dorsolateral prefrontal cortex has no observable effect on the accuracy or reaction time of a standard FTT. In contrast, cathodal tDCS led to a significant improvement in reaction time, increasing the speed by which participants tapped out a sequence of keys on the Post-test compared to the Pre-test. Even though a majority of articles and research suggests that there is either a null effect or an impairment on motor performance following cathodal stimulation of the dorsolateral prefrontal cortex, those studies tended to focus anodal stimulation with the placement of the cathode being seemingly arbitrary.

Table 3 represents an attempt to highlight similarities and differences in findings compared to the present work. While it is true that some studies have reported a facilitatory effect of cathodal stimulation, more work is necessary to determine why other studies (and theoretical perspectives) have come to the opposite conclusion. Below, I lay out a number of possible ways of reconciling the seemingly inconsistent findings in the literature.

Possibility 1: Cathodal tDCS Improves Finger Movements

Based on the results, it is possible to assume that the Cathodal tDCS can actually improve the finger movements. While the placement of the anode is well known to affect the cortical excitability of the underlying brain (Varoli et al., 2018), a smaller literature also suggests that the area of the brain under the cathode either increases or decreases in cortical excitability, depending on its relative placement on the scalp. For instance, Knotkova et al. (2017) reported

that when the cathode is located over DLPFC, and the anode is located over Fp1, the DLPFC's cortical excitability increases under the cathode. As mentioned in the introduction section, enhanced cortical excitability of the DLPFC has been associated with motor improvements (Ohashi, Gribble & Ostry, 2019)--though the increased excitability in that previous study was induced by anodal stimulation of the DLPFC).

On the other hand, when the electrodes are moved to the occipital lobe, with the anode and the cathode placed over opposing hemispheres, these authors reported that cortical excitability under the cathode is suppressed. From this, one can conclude that the relative placement of both the anode and the cathode in part determine the direction of cortical excitability under the cathode. Meanwhile, the Anodal tDCS showed a similar effect as the Cathodal while locating in Fp1 and O1 (The cortical excitability improved in Fp1 and decreased in O1) (see Figure 16 as an example).

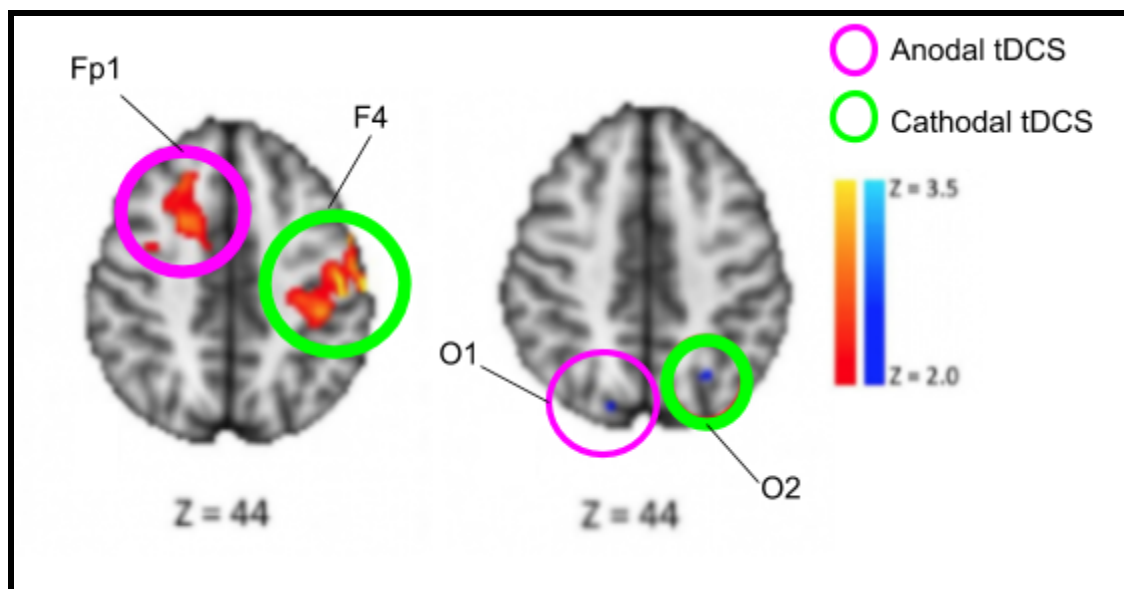


Figure 16 Cortical excitability as a function of cathodal placement adapted from Knotkova et al. (2017). The anode located region showed in purple circle and the cathode located region showed in green circle. The left panel depicts the cortical excitability (significant increases over 2.0 in hot colors) a combination of Cathodal tDCS over F4 and the Anodal tDCS over Fp1. The right panel

depicts a combination of Cathodal tDCS over O2 (in green circle) and Anodal tDCS over O1. This cold color mark in the green circle reveals that the Cathodal tDCS in O2 suppressed cortical excitability significantly and anode in O1 suppressed cortical excitability as well. ($Z = 44$ indicates which horizontal slice of the brain--here the 44th--is depicted within the normalized brain image)

Possibility 2: Bilateral tDCS Montage can Affect the Motor Performance Differently with Unilateral tDCS

The previous section highlighted how the placement of the anode and cathode over different regions of the brain may affect cortical excitability and task performance in different ways. In some cases, the anode and the cathode are placed in a symmetrical manner--with one on the analogous region of the corresponding hemisphere. This has been referred to as bilateral tDCS. In contrast, when the electrodes are placed above non-corresponding regions of the brain, this has been referred to as unilateral tDCS. See Figure 17 for a comparison.

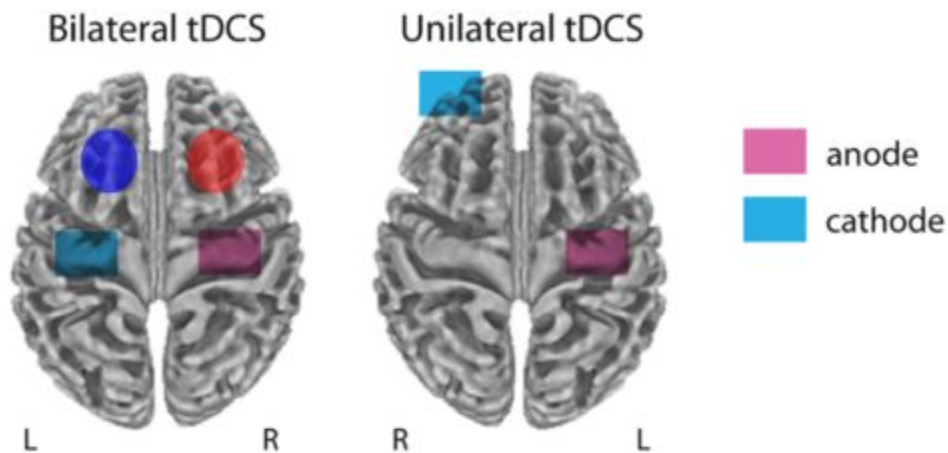


Figure 17 An example of the Bilateral tDCS and Unilateral tDCS model. In the Bilateral tDCS, the dark blue and red circles are the locations where my project targeted (F3 & F4).

Prior studies showed that the bilateral tDCS over M3 and M4 tended to enhance the motor cortex plasticity and the cross-transfer of strength which implied that the bilateral tDCS over DLPFC facilitated greater improvements in motor performance in both Anodal tDCS and Cathodal tDCS (Frazer, Kidgell, Spittle & Williams, 2016) (Vine, Cerruti & Schlaug, 2008). In contrast, the unilateral tDCS, with the anode placed over M1 and cathode placed over M4, revealed that only the the Anodal tDCS had an improving effect in the RT of FTT and a decreasing effect in Cathodal tDCS condition. This is probably why most studies with unilateral tDCS related motor tasks can only detect the significantly improved performance in Anodal tDCS. Since my tDCS montage was designed as a bilateral tDCS, I also consider this as a possibility.

The RT of the left hand from my study can be used as another support. In my study, even though I focused on the result of the dominant hand (right hand), the data of the left hand was also collected. In the left hand result of my study, it showed the same effect as the right hand result. The Cathodal tDCS over right DLPFC (left hand) showed a significant improvement ($F(1,19), p = 0.02$) in RT between pre-test and post-test. Also, comparing the RT post-test data among the three conditions, the Cathodal tDCS had a significantly faster RT than Sham tDCS ($F(1,19), p = 0.03$). The result supported this possibility that in a bilateral tDCS montage, the Cathodal tDCS can improve the motor task (See Figure 18 for the results of the left hand RT).

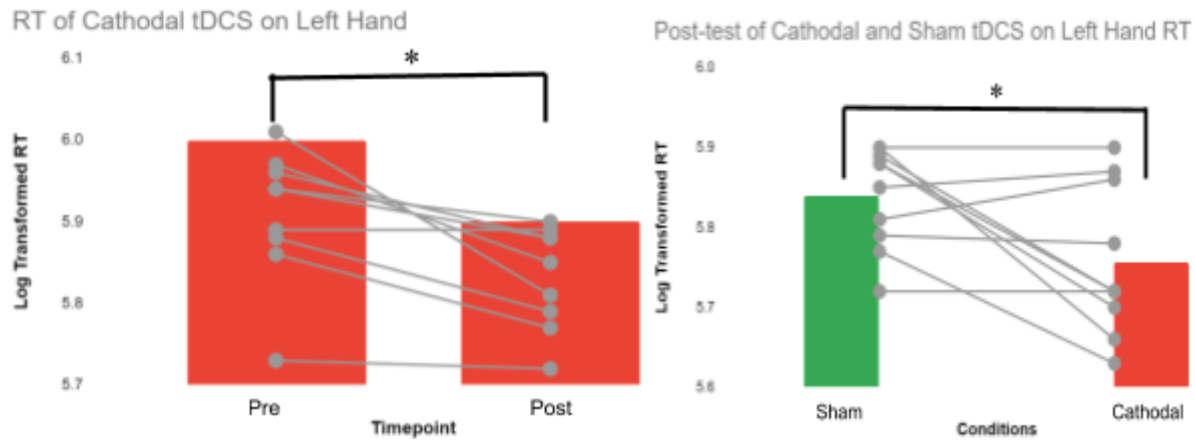


Figure 18 The RT of cathodal tDCS on left hand is presented on the left. The grey lines are all participants' pre-test and post-test. The post-test of cathodal and sham tDCS on the left hand is presented on the right. The grey lines are participants post-test score of RT from Sham and Cathodal conditions.

Possibility 3: Suppression of the Cortical Excitability can Enhance Performance on Motor Tasks.

To see the changes underneath the brain, such as cortical excitability and motor evoked potentials (MEPs), other devices like functional Magnetic Resonance Imaging (fMRI), magnetoencephalography (MEG), and electroencephalography (EEG), is needed. However, there is no support of thi type in my study, so we can not really tell what the rate of the cortical excitability and MEPs look like while participants the stimulation. In the first two possibilities I mentioned above, the theories were based on the assumption that cortical excitability of the targeted cathode region was improved. However, what if the cortical excitability is suppressed? Another interesting finding by Alana et al. in 2011 indicated that, while cathodal tDCS over area M1 did suppress cortical excitability in primary motor cortex (did not mention where the anode

tDCS placed), that suppression was associated not with an impairment in motor ability but an enhancement of the dominant upper limb (including the, right arms, hands, and fingers). The suppressed cortical excitability of Cathodal tDCS keeps the cortical excitability in balance which has better cooperation between the fingers and the stimulation trials (Alana et al., 2011). This gave a possibility that sometimes when participants were doing the FTT, to get a better score in RT and ACC, they may start to get nervous and try to do there best (e.g some participants were so into the study that they said they want to get every blocs in a fast and 100% accuracy). This psychology activity may increase the cortical excitability into an excessive level. The score may be lower than the average instead. However, the cathodal tDCS over the left DLPFC suppressed the overloaded cortical excitability and made it back to the normal level. This process kept the cortical excitability in balance that lead to a better FTT score since a calmer brain can have a better motor function.

Besides the possible reasons why Cathodal tDCS may have an unexpected effect, there also have some limitations of the study that could have led to the observed pattern of results.

Limitation 1: The Design is Underpowered

As mentioned in the Method section, due to the force majeure, this study's planned sample size (already quite small), had to be further reduced (N = 10), resulting in a highly underpowered study. A study with low statistical power not only has a reduced chance of detecting a true effect. There are nine Asian and one Lantino participants recruited in this study. This can not represent the population at Bard. The reason why this happened is due to a snowball

effect that the first two participants were Asian and they helped to recruit their friends to do this study (see Table x in **Results** section).

Other elements of the present study's design, e.g., the relatively weak current, short stimulation duration, and the small number of FTT trials that went into the calculation of average performance might have led to noisy measures, false negatives and/or false positives. In most study designs in tDCS study in literature, they usually use a stronger current and longer stimulation duration to see changes in behavior owing to the stimulation. The ideal design of this type of study is to have 2.0 mA current with a 20 minutes simulation duration (D ' Atri et al., 2015). With a longer duration, the FTT can have more trails in each session that make the average score of the participants more accurate. In this study, each participant received 40 trials x 3 times in each session. In prior research that related to FTT and tDCS, the ideal number of test trials at each time point would be around 80 trials minimum which provided a better image of participants' average performance (Nitsche et al., 2003). However, the IRB of Bard College has not previously attempted this type of study. To minimize the risk of the side effect of the tDCS, the feasibility and safety of the study were considered, in which at the end the study used only 1.0 mA current and 10 minutes duration. This may make the changes in cortical excitability and neuroplasticity hard to detect and result in a smaller chance of finger movement ability to be affected even though there is some existing evidence in the literature that with this level of stimulation, the changes can still be detected (see Table 3 for references that used the different levels, duration times of tDCS, and amount of FTT trails).

Studies (Year)	Motor Task	Hand tested	N per group	Montage of reference electrode	Current density/ duration	Task Trials
Nitsche et al. (2003)	SRTT	Right	20	Contralateral	1 mA/ 15 min	8 blocks; 120 trials each
Reis et al. (2009)	SRTT	Right	12	Contralateral	1 mA/ 20 min	45 min; 200 trials
Galea et al. (2011)	Visuomotor adaptation	Right	10	Contralateral	2 mA/ 20 min	25 blocks x 200 trials
Schambra et al. (2011)	FTT	Right and left	14	Ipsilateral	1mA / 20 min	6 blocks x 200 trials
D' Atri et al. (2015)	FTT	Right and left	20	DLPFC	2mA/ 20 min	3 session x 200 trials
Antal et al. (2011)	FTT	Right	26	SMA, PM, and M1	1mA / 20 min	80 blocks; 20 seconds each

Table 3 Summary of tDCS studies stimulation aiming to improve the finger tapping related task in healthy populations (all in right-handed participants).

Limitations 2: The tDCS Technique Is Not Mature Enough

Even though tDCS is one of the most commonly used devices to stimulate cortex, the limitation also exists. Compared to TMS, tDCS uses sponges with saline water to induce the current over the cortex. The range of the targeted brain region can not be precisely located and the current can also affect the brain region next to the target area. Thibaut et al (2017) mentioned in his study that tDCS modulates not only the area stimulated but also the entire neural network. For instance, by means of neuroimaging studies (fMRI and Positron Emission Tomography—PET), anodal M1 tDCS has been shown to activate ipsilateral motor areas (e.g.,

primary, supplementary, or premotor cortices) as well as contralateral or long-distance areas (e.g., frontal cortex, somatosensory regions, posterior parietal cortex) and subcortical areas (anterior cingulate cortex) in participants (Lang et al., 2005; Kwon et al., 2008; Kim et al., 2012). Also, the effect of tDCS can be varied on different subjects depending on the head size and the distance between scalp and brain (Kantkova et al., 2017). For example, participants who have a smaller head size will have a higher increasing rate of cortical excitability than participants with bigger head size. This situation was not considered in my study design since it is really hard to control and find a group of participants with similar head size.

Moreover, for the current study, to save the money, I did not prepare a device to detect the motor evoked potential rate which made the results ambiguous, in that I was unable to ascertain there is really a change in the underlying brain regions' cortical excitability following stimulation.

Future Directions and Applications

To improve our understanding of how brain stimulation techniques such as tDCS and TMS function, future studies should include the measurement of MEPs to see the invisible changes under the scalp. Better tDCS protocol and study design also need to come up to make sure the practice effect and other possible outlier makers can be ruled out. This can be done by doing a between-subject design that one group of participants only do the FTT with sham tDCS and another group only do it with active tDCS. This requires a larger sample size since the motor skills of each person are varied. Moreover, since I am in the five-year double degree program in

Bard Conservatory, I would like to re-run this study with a larger sample size and longer duration of the tDCS stimulation duration in my remaining time at Bard.

Conclusion

Generally, this study revealed that the Cathodal tDCS over the Left DLPFC region (F3) can actually improve the speed of the finger performance in the dominant hand. This finding gives a new idea 'challenge the stereotype of the Cathodal tDCS that it's not more important than Anodal tDCS and always has a impaired effect on motor performances. In the future, the function of the Cathodal tDCS should be explored more and maybe can be commonly used in many fields as Anodal tDCS.

tDCS as a user-friendly, portable, relatively non-invasive stimulation device is popularly used nowadays in so many forms. Some commercial tDCS devices focus on improving sleep quality, smoking prohibition, reflection, and movement memorizations, and so on. Also, it can be used to help patients with rehabilitation motor abilities after the stroke. I believe in the future, with the greater popularity and understanding of this technology, our living quality, and working efficiency can be improved a lot.

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Appendices

Appendix A: IRB Proposal

Appendix B: Inclusion and exclusion criteria

Appendix C: Advertisement Flyers for Recruitment

Appendix D: Consent Form

Appendix E: tDCS Screening Questionnaire

Appendix F: tDCS Post Experiment Questionnaire

Appendix G: NIH human participant protection education certificate

Appendix H: Debriefing statement

Appendix I : Left hand results of FTT

Appendix A: IRB Proposal

SECTION 1

1. **Last name:** Zhang
2. **First Name:** Zongheng
3. **E-mail:** zz2302@bard.edu
4. **Phone number:** 845-366-9315
5. **Academic program:** Psychology
6. **Status:** Student
7. **Name of faculty advisor/sponsor:** Justin Hulbert
8. **Adviser's/sponsor's e-mail:** jhulbert@bard.edu
9. **Today's date:** 11/4/19

SECTION 2

1. **I have read the IRB's Categories of Review, and my proposal qualifies for a:** Full Review
2. **Do you have external funding for this research?** No
 - a. **If so, state name of granting institution:** Not applicable
3. **Begin date:** Upon approval
4. **End date:** Ongoing, pending regular IRB reviews
5. **Title:** The Effect of Cathodal tDCS on Motor Skills

Research question:

Does the direction of the current flow using transcranial direct-current stimulation (tDCS) affect one's ability to perform motor tasks? tDCS, a form of neurostimulation, was originally developed as a treatment for psychiatric disorders, such as depression, schizophrenia, and obsessive-compulsive disorder (OCD; Moffa, Brunoni, Nikolin, & Loo, 2018). Around twenty years ago, tDCS emerged as a safe, and relatively low-cost non-invasive brain stimulation (NIBS) technique with research pointing to the potential for it to improve a range of behaviors, including motor coordination, vigilance, and learning (Priori et al., 1998; Hannah, Iacovou, & Rothwell, 2018). This is achieved by placing two electrodes--one positive (the **anodal+**) and one negative (the **cathodal-**) on the scalp, and running current across them. This has the effect of stimulating the underlying brain regions by altering cortical excitability (Javier Márquez-Ruiz et al., 2012). Increasing neuronal excitability has been associated with the temporary enhancement in skills supported by the targeted regions (Schlaug & Renga, 2008). The behavioral consequences of neuronal inhibition associated with cathodal stimulation are less well understood, though it has been known to temporarily impair performance (Roe et al., 2016). For instance, anodal stimulation over the right primary motor cortex

reportedly improved performance on a so-called pegboard task (involving the placement of pegs in a particular arrangement as a measure of unimanual and bimanual finger/hand dexterity)). Regions beyond the motor cortex are known to be involved in motor performance, as well. Based on prior research, anodal tDCS over the left dorsolateral prefrontal cortex region (roughly, the left forehead), for instance, yields temporary, though reliable, improvements in motor skills, including finger-tapping and pegboard tasks.

Systematic explorations of the behavioral consequences of neuronal inhibition associated with cathodal stimulation (i.e., reversing the polarity of the electrodes) remain relatively rare. Oftentimes, the cathode's placement on the scalp is a matter of convenience, rather than a topic of interest. And some researchers suggest that cathodal tDCS over a target region has the same behavioral consequences as anodal tDCS (Monti et al, 2008). As one exception, Christova, Rafolt, & Gallasch (2015) reported that cathodal stimulation over the primary motor cortex temporarily impaired motor performance, in that reaction times to complete the task were increased significantly (Christova, Rafolt & Gallasch, 2015). To our knowledge, it remains unknown whether cathodal stimulation of the dorsolateral prefrontal cortex has the same effect. To contribute to the ongoing debate over the influence of cathodal stimulation, as well as to our developing understanding of the dorsolateral prefrontal cortex's role in motor functioning, my Senior Project aims to test whether cathodal tDCS over the left dorsolateral prefrontal cortex reverses the benefits seen in anodal stimulation of this region (compared to a control/sham condition, in which a 1.0 mA current will be delivered for approximately 30 seconds before being extinguished over a course of seconds, which produces a sensation similar to that experienced by continuous stimulation but without the sustained effects).

6. Will your participants include individuals from specific populations (e.g., children, pregnant women, prisoners, or cognitively impaired)?

No

7. If your participants will include individuals from specific populations, please specify the population(s) and briefly describe any special precautions you will use. Not applicable

8. Briefly describe how you will recruit participants (e.g., Who will approach participants? What is the source of the participants?).

Participants recruited under this proposed protocol would be healthy right-handed adults who are free of diagnosed neurological/attentional/learning disabilities, brain injuries, between the ages of 18-30. Additionally, they should have a normal/corrected-to-normal color vision. Participants will also need to be willing/able to have felt tDCS sponges moistened with a saline solution (to allow for electrical conduction), introduced on their hair/scalp while sitting relatively still and performing simple motor tasks. A standard screening questionnaire will be used to determine eligibility prior to the study (see **Appendix E**)

Recruitment materials (posters, flyers, messages distributed via electronic bulletin boards/listservs/social media, and/or advertisements placed in local online/printed periodicals—see **Appendix C**) will direct interested parties to contact the researcher at zz2302@bard.edu for additional screening checks and more information.

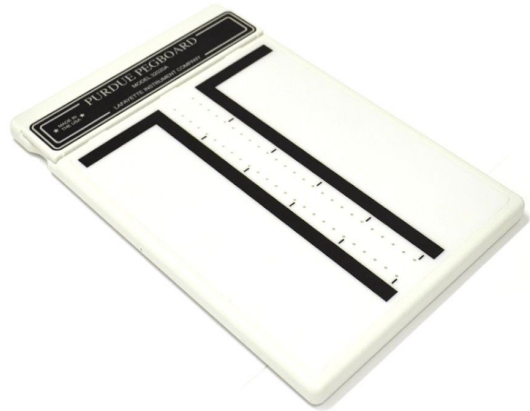
Upon the first contact, recruits will be asked to confirm their eligibility for the particular study in question and their desire to participate. Following this, they would have the opportunity to schedule an appointment. Upon arrival at their scheduled appointment, participants would again go through a written eligibility screening measure (to serve as a triple-check) after undergoing the informed consent process (see **Appendix D** for the language used in these materials). Participants will be entitled to \$7 for their participation in the multi-part study, paid at their final visit.

- 9. Briefly describe the procedures you will be using to conduct your research. Include descriptions of what tasks your participants will be asked to do, and about how much time will be expected of each individual. NOTE: If you have supporting materials (recruitment posters, printed surveys, etc.) please email these documents separately as attachments to IRB@bard.edu. Name your attachments with your last name and a brief description (e.g., "WatsonConsentForm.doc").**

In addition to undergoing the screening, participants will be invited to Preston Hall a total of four times. The first time meeting will take 10 minutes, which will ask participants to do the screening questionnaire to confirm the eligibility and sign the consent form. The next three meetings will be (for approximately 25-30 minutes each time) for the experiment proper. In order to account for potential time-of-day effects, the three main visits ideally would be scheduled either 24 or 48 hours apart from each other, depending on participant/researcher availability. At each visit, their task performance will be measured before, during, and after anodal, cathodal, or sham stimulation. The order of the three stimulation conditions will be counterbalanced across participants. The proposed design will allow me to evaluate the effects of anodal, cathodal, and sham tDCS for each subject (i.e., a within-participants, cross-over design).

At the beginning of each visit, participants will first be fitted with a swimming cap with markers used to identify the rough location of underlying brain regions of interest. Then, two electrodes will be placed over the participant's scalp on top of conductive sponges (moistened in a saline solution) at locations roughly above the left and right dorsolateral prefrontal cortex. The electrodes and sponges will be secured with a comfortable headband. Then participants will be instructed to complete a basic motor task that asks them to insert pegs into a board at certain locations (see

Appendix A for more information about the task). In short, the Purdue Pegboard (see Figure 1) was developed in the 1940s as a test of manipulative dexterity for use in personnel selection (Tiffin, 1968; Tiffin & Asher, 1948). The board consists of two parallel rows of 25 holes each. Pins (pegs) are located at the extreme right-hand and left-hand cups at the top of the board. Collars and washers occupy the two middle cups. In the first three subtests, the participant places as many pins as possible in the holes, first with the preferred hand, then with the non-preferred hand, and finally with both hands, each within a 30-s time period. To test the right hand, the participant is asked to insert as many pins as possible in the holes, starting at the top of the right-hand row. The left-hand test uses the left row. Both hands then are used together to fill both rows top to bottom. In the fourth subtest, the participant uses both hands alternately to construct “assemblies,” which consist of a pin, a washer, a collar, and another washer. The subject must complete as many assemblies as possible within 1 minute.



(Figure 1)

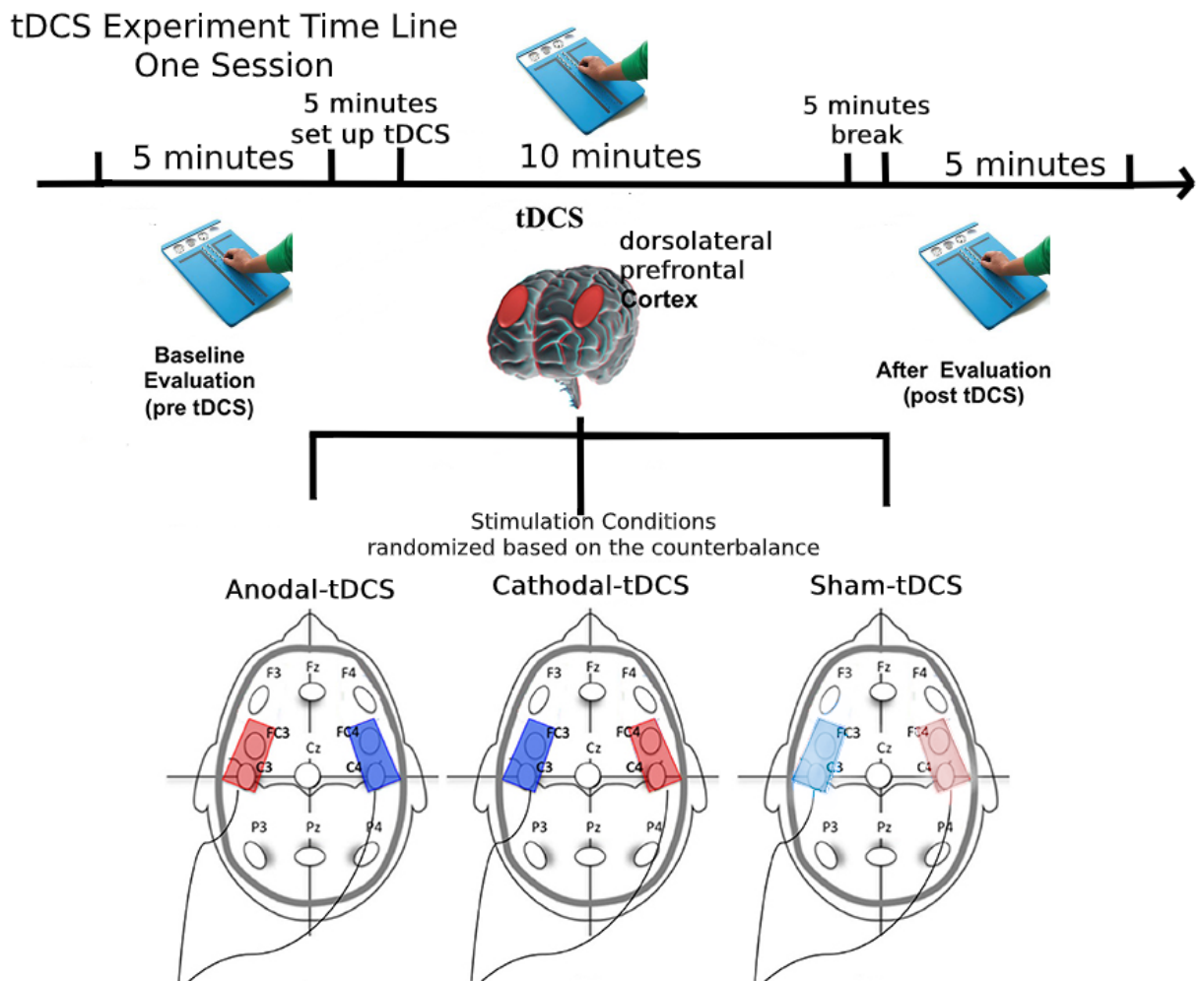
Sponges will be retained for a particular participant’s use across the three visits (sanitized after each visit and stored in a sealed Ziploc bag); however, a different set of sponges will be used for each participant. The swimming cap is sanitized after each visit, following standard lab procedures (see, e.g., Bard IRB protocol 2016NOV16-HUL).

I plan to use the Brain Driver company’s tDCS Device V2.1 (<https://thebraindriver.com>; see Figure 2) for the purposes of my investigation. This commercially available device allows the operator to establish the current strength and stimulation duration. It is powered by a 9-volt battery, limiting any risk. In the anodal and cathodal conditions, participants will receive 1.0 mA tDCS stimulation for 10 minutes while doing the Pegboard Tasking. Based on prior studies, any behavioral effects

introduced by this level of stimulation will be short-lived, without any long-term effects (Hao Li et al., 2015).



(Figure 2)



(tDCS Experiment TimeLine One Session)

10. Approximately how many individuals do you expect to participate in your study?

Based on counterbalancing factors, statistical power, and potential attrition over the three lab visits, I expect I will need approximately 30 participants to complete the experiment. Data collection will be ongoing throughout the year and may continue through future renewals of this protocol, subject to IRB review and approval.

11. Please describe any risks and benefits your research may have for your participants. (For example, one study's risks might include minor emotional discomfort and eyestrain. The same study's benefits might include satisfaction from contributing to scientific knowledge and greater self-awareness.)

Safety of tDCS: tDCS has been used with thousands of patients worldwide in a variety of clinical, research, (and even recreational) settings. Consumer devices are now heavily marketed on sites such as Amazon and Halo Neuroscience, reflecting the increased interest in the technology and a proven safety track record. Brunonni et al., (2011) reported that the rate of side effects is comparable between those receiving active and sham stimulation. We will follow established safety guidelines provided by Thair, Holloway, Newport, and Smith (2017). Few, if any, side effects are reported with our chosen parameters (current strength and duration) with an eligible, healthy participant population. Moreover, reported side effects (rare that they are) are mild in nature (e.g., tingling, itching, or, in exceptionally rare cases, what is described as a mild burning sensation that ends once the stimulation has ceased Nitsche & Paulus, 2011). In addition, to carefully screen out potential participants with characteristics that might increase the likelihood of these side-effects, my supervisor and I will rigorously monitor participants' comfort and safety throughout the procedure, as well as administer a standardized assessment of any potential tDCS-related adverse effects using the questionnaire to each participant finishes (**Appendix F**).

12. Have you prepared a consent form and emailed it as an attachment to IRB@bard.edu? Yes**13. Please include here the verbal description of the consent process (how you will explain the consent form and the consent process to your participants):**

Recruits will initially be told that the study is investigating how electrophysiological signals correspond to their ability to perform motor tasks. They'll be informed that the experimenter will provide them with all the necessary instructions and walk them through each step of the experiment, as well as a full debriefing after the experiment is over. After confirming that they are eligible for the experiment, the experimenter will then provide a brief oral description of the tasks they'll be asked to perform and equipment to be used during the experiment. They will be shown the equipment and given a description of how it will be used in the experiment to make sure that they are comfortable with the equipment and procedures. Should they indicate their willingness to participate, all participants will be provided a written informed consent agreement that describes the study in more detail. They will then be asked to repeat back, in their own words, the procedure laid out in the consent form and to verbally answer a set of basic questions establishing their understanding and their right to withdraw from the study at any point without penalty. Provided all parties reach a common understanding, the participant will be invited to sign the consent agreement. All participants will be told that they are welcome to ask questions about the experiment both before and after the experimental session and pointed to the additional contact information provided on the consent/debriefing forms.

14. If your project will require that you use only a verbal consent process (no written consent forms), please describe why this process is necessary, how verbal consent will be obtained, and any additional precautions you will take to ensure the confidentiality of your participants. Not applicable

15. What procedures will you use to ensure that the information your participants provide will remain confidential?

Aside from a single document linking participant names and contact information to their arbitrary participant number (to allow for the multiple visits), which will be kept on campus in a secure, password-protected file and destroyed upon the submission of my Senior Project, all of the data collected in this study will be coded in an unidentifiable manner (using only an arbitrary number string to identify linked data) and kept strictly confidential. Individually identifiable data will not be released to anyone outside the research laboratory without the written consent of the participant. Data (stripped of individuating information) will be stored in password-protected computer files, accessible only to members of the research team that is certified to work with human subjects. If any information obtained from this study is published, the article will be written so that the identity of all subjects will remain confidential. Signed consent forms will be stored separately from the data, in a locked filing cabinet accessible only to

members of the research team that is certified to work with human subjects. All study materials will be coded and entered into password-protected computer files. Any publication or conference presentation stemming from the research in question would avoid the inclusion of any identifying participant information.

16. **Will it be necessary to use deception with your participants at any time during this research? Please note: withholding details about the specifics of one's hypothesis does not constitute deception. However, misleading participants about the nature of the research question or about the nature of the task they will be completing does constitute deception.** Yes

17. **If your project study includes deception, please describe here the process you will use, why the deception is necessary, and a full description of your debriefing procedures.**

Participants will not be told that they are receiving a sham stimulation until after the completion of the study. In this condition, a 1.0 mA current will be delivered for approximately 30 seconds before being slowly extinguished over a course of seconds (the electrodes will be placed over the same regions of the brain as in the experimental condition and the anodal and cathodal electrodes will be randomized placed based on the counterbalancing). Most participants cannot distinguish between real and sham tDCS, as they habituate to the sensation of the stimulation after a short time period. Given that participants may have certain expectations about the possible effects of tDCS, we are utilizing the sham condition as a control to allow us to separate out any such expectancy effects.

18. **For projects not using deception, please include your debriefing statement. (This is information you provide to the participant at the end of your study to explain your research question more fully than you may have been able to do at the beginning of the study.) All studies must include a debriefing statement. Be sure to give participants the opportunity to ask any additional questions they may have about the study. See Appendix H for a sample debriefing statement.**

SECTION 3

1. **If you will be conducting interviews in a language other than English, will you conduct all of the interviews yourself, or will you have the assistance of a translator?** Not applicable.

2. **If you will be using the assistance of a translator, that individual must also certify that he or she is familiar with the human subject protocol and has completed the online training course. Please respond whether you have found an IRB-certified translator. Not applicable.**
3. **If you have not yet found a translator, do you agree that when you do find a translator, you will make sure that person will also agree to use the standard protocol for the treatment of human subjects and that the individual's training certificate will be submitted to the IRB records before you begin collecting data? Not applicable.**
4. **If your recruitment materials or consent forms will be presented in languages other than English, please translate these documents and email copies as attachments to IRB@bard.edu. Not applicable.**
5. **I have submitted all my translated materials. Not applicable.**
6. **I have submitted a copy of my video consent form. Not applicable.**

SECTION 4

1. **If you are a graduate or undergraduate student, has your adviser seen and approved your application? Yes.**
 - a. **If you have not already done so, you must ask your adviser to email a statement on your behalf to IRB@bard.edu. The statement should read, "I have reviewed [your name]'s proposal and I will oversee this research in its entirety."**
2. **Please read the following statement carefully: "I have read the Bard IRB policy on the treatment of human research participants. I will comply with the informed consent requirement, and I will inform the IRB if significant changes are made in the proposed study. I certify that all of the information contained in this proposal is truthful." Submitting this form means that you affirm the statement above and will comply with the content. This counts as your legally binding signature.**

I concur with the above,

Signature: Zongheng Zhan

Appendix B : Inclusion and exclusion criteria**Inclusion Criteria**

1. Neurologically healthy right-handed adults, age 18-30 years old, with no motor deficits and normal/corrected-to-normal vision
2. Willing and able to provide informed consent for the tDCS and behavioral procedures
3. Willing to participate in multiple (3) study visits (following screening), each lasting 25-30 minutes each

Exclusion criteria

1) History of adverse reaction to tDCS
2) History of or current treatment for seizures
3) Self-reported scalp sensitivity (e.g., excessive dryness that requires the use of specialized shampoo for sensitive scalps)
4) History of neurosurgery involving the brain
5) Current use or use within the past 6 weeks (from any of the experiment sessions) of medications known to particularly affect dopamine or serotonin reuptake (most commonly, antidepressants), dopamine release (e.g., medications for attention-deficit/hyperactivity disorder), dopamine receptor activity (e.g., antipsychotics, also used as augmenting agents in the treatment of depression and as mood stabilizers in bipolar disorder) or GABA function (e.g., benzodiazepines, but use of short-acting non-benzodiazepine sleep medications such as zolpidem [e.g., Ambien] will be allowed)

6) Current treatment with any anticonvulsants (carbamazepine (Tegretol), oxcarbazepine (Trileptal) lamotrigine (Lamictal), Divalproex (Depakote), topiramate (Topamax), levetiracetam (Keppra) or with lithium (lithium or Eskalith)
7) Current use of bupropion (Wellbutrin, Wellbutrin SR, Wellbutrin XL, Zyban, Aplenzin, Fortivo XL, and Zyban)
8) Lack of sleep (less than 6 hours the night before a laboratory session)
9) History of bipolar disorder or a history of mania or hypomania of any type.
10) Surgically implanted pacemaker
11) Any metal embedded the head (e.g., shrapnel, surgical clips, or fragments from welding)
12) Any alcohol intake 24 hours before the study

Appendix D: Consent Form**INFORMED CONSENT AGREEMENT****Protocol number:****Expires:****Study title:** The Effect of Cathodal tDCS on Motor Skills**Student Researcher:** Zongheng Zhang**Faculty adviser:** Justin C. Hulbert, Ph.D.

You are being asked to take part in a research experiment conducted at Bard College as part of a Senior Project in Psychology that seeks to assess whether transcranial direct current stimulation (tDCS) can influence the motor ability in healthy people.

To decide whether or not you wish to participate, you should know enough about its risks and benefits to make an informed judgment. This consent form gives you information about the research study, and the experimenter will provide you with additional information about the specific tasks that you will be performing. Once you are ready, you will be asked if you wish to participate and, if so, you will sign the consent form. You can choose not to participate, and you can choose to end your participation at any time during the study.

Background: Transcranial Direct Current Stimulation (tDCS) is a non-invasive brain stimulation technique that involves applying a very weak electrical stimulation to the brain using a battery-operated machine (the equivalent of a 9-volt battery). Stimulation is delivered via two conductive sponges applied to the scalp using moistened sponges. A weak current is passed between the electrodes to stimulate specific parts of the brain, as changes to one's motor abilities are monitored.

What you will do in this study: Should you be eligible and decide to participate, you will be invited to Preston Hall three times (for approximately 25-30 minutes each time). At the beginning of each visit, you would first be fitted with a swimming cap, which will allow us to identify the spots on your head where we will place two moistened sponges attached to electrodes. The electrodes and sponges (dampened with a salt-water solution) will be secured using a comfortable headband. Then you would be asked to perform a simple motor task, involving the insertion of a number of pegs into a board at certain locations.

The researcher will offer detailed instructions to guide you through each part of the experiment and answer any questions you may have about the procedure. After the experiment, you will then be asked to fill in a brief questionnaire about your experience and given an opportunity to ask any remaining questions that you may have.

Risks and benefits: tDCS is considered to be a safe technique, but there are some known risks, which are described below. The most common side effect (reported by 70% of participants) is that of a tingling sensation under the electrodes. This may be present during and shortly after the period of stimulation but has no long-term adverse effects or risks. Fatigue or tiredness, during the stimulation, is the next most commonly reported side effect (experienced by approximately 35% of participants), and this may continue for a short period afterward the stimulation has ended (around 10-15 minutes). However, fatigue is not uncommon in everyday life, as it may occur following any prolonged task (such as studying). Headaches after stimulation may occur in less than 10% of the participants. Headaches are usually mild and can be treated with over-the-counter painkillers, should the participant so elect to do so on their own. There is no evidence that tDCS leads to any change in the frequency or severity of headaches. Overall, 80% reported that it was not unpleasant, less than 20% of the participants rated the stimulation procedure as mildly unpleasant. In theory, tDCS might induce seizures in populations that are predisposed to the condition, but this has never been reported in the scientific literature. Furthermore, we follow a rigorous screening procedure to minimize the risks to participants.

If you find yourself uncomfortable or would like to end your participation in the research at any point, you have the right to do so. Just tell your experimenter, “I want to stop,” and you will be free to leave without penalty.

If you are a student at Bard College and find that any aspect of the experiment caused you distress, you are encouraged to contact the Bard Counseling Center at 845-758-7433 during normal business hours or at 845-758-7777 after hours or on weekends.

While this research experiment may not provide participants with any direct benefits, the data collected from this study may help improve the scientific understanding of how mild electrical stimulation may affect people’s cognition and motor performance. Moreover, the researchers hope that participants gain insight into the research process at Bard College through their involvement with this work.

Compensation: In exchange for participating in this experiment, you will be eligible to receive \$7, delivered after your final session.

Your rights as a participant: Your participation in this experiment is completely voluntary, and you may withdraw from the experiment at any time without penalty. You will still receive compensation for participating up to that point. You may withdraw simply by informing the experimenter that you no longer wish to participate.

Confidentiality: All information that is collected about you during the course of the research will be kept strictly confidential, stored in a secure and locked office,

and on a password-protected database. The study data collected will be reviewed by the Senior Project student running the study, his Senior Project advisor, and the other Bard faculty members supervising his work.

The results of this study may be used in research, publications, or presentations at scientific meetings, including the student researcher's Senior Project, which will be available in the Stevenson Library and via the Digital Commons (a searchable online database used by the Bard Library system). However, individual participants will not be identified.

STATEMENT OF CONSENT:

"I understand the purpose of this research. My participation in this research is voluntary. If I wish to stop the interview for any reason, I may do so without having to give an explanation.

The researcher has reviewed the relevant risks and potential direct/indirect benefits with me, to the extent there are any. I am aware the information will be used in a Senior Project that will be publicly accessible online and at the Stevenson Library of Bard College in Annandale, New York."

By signing below, I agree with the above **statement of consent** and further certify that I am at least 18 years of age.

Participant signature

Date

Participant name (printed)

Appendix E: tDCS Screening Questionnaire*(Adapted from Reidler, 2014)*

Please read through all of the questions below before answering. It is crucial that you answer honestly so that we may determine whether you are eligible to participate in this experiment safely. For your privacy, we are asking only for a single response about your overall eligibility, rather than an individual response to each question.

Consider whether you have ever:

1. Had an adverse reaction to tDCS?
2. Had a seizure?
3. Had a stroke?
4. Had a serious physical head injury?
5. Had surgery to your head?
6. Had any brain-related neurological disorder?
7. Had any illness that may have caused brain injury?
8. Suffer frequent or severe headaches?
9. Have any metal in your head such as shrapnel, surgical clips, or fragments from welding?
10. Have any implanted medical devices such as cardiac pacemakers or medical pumps?
11. Have diagnosed motor deficits?
12. Have diagnosed bipolar disorder, mania or hypomania of any type?
13. Have a sensitive scalp (e.g excessive dryness)?

Additionally, are you:

14. Pregnant, or are you sexually active and not sure whether you might be pregnant?
15. Blood-related to anyone who is known to have epilepsy?
16. Taking medications: antidepressants, antipsychotics, benzodiazepines, zolpidem, carbamazepine (Tegretol), oxcarbazepine (Trileptal) lamotrigine (Lamictal), Divalproex (Depakote), topiramate (Topamax), levetiracetam (Keppra) or with lithium (lithium or Eskalith), Wellbutrin, Wellbutrin SR, Wellbutrin XL, Zyban, Aplenzin, Fortivo XL, and Zyban?
17. Consider yourself to be left-handed or ambidextrous?

Please check "YES" below if your answer to ANY of the above questions (1-15) is in the affirmative (otherwise check "NO"). Again, for your privacy, we are not asking you to specify which question(s) might be true for you; however, it is CRITICAL for your safety that you answer honestly and accurately. If you are unsure of an answer, please check "YES," just in case or ask the experimenter for clarification.

Yes

No

Appendix F: tDCS Post Experiment Questionnaire

Participant Number: _____

Session: _____

Date: _____

<p>As a result of the tDCS session, did you experience any of the following symptoms or side effects?</p>	<p>For each row, enter the appropriate value (1-4). 1 - Absent 2 - Mild 3 - Moderate 4 - Severe</p> <p>If you did not experience the effect, enter a 1.</p>	<p>If you experienced any of the side effects, please describe below.</p>
Headache		
Neck Pain		
Scalp Burns		
Tingling		
Skin Redness		
Sleepiness		
Trouble Concentrating		
Acute Mood Change		
Other (specify):		

Appendix G: NIH human participant protection education certificate



Appendix H: DEBRIEFING STATEMENT

Study Title: The Effect of Cathodal tDCS on Motor Skills

Senior Project Student: Zongheng Zhang

Faculty Advisor: Justin C. Hulbert, Ph.D. (Psychology Program, Bard)

This study was designed to investigate the effects of tDCS on the cortex excitability and the corresponding ability to perform motor tasks. Transcranial direct-current stimulation (tDCS), is a non-invasive brain stimulation technique. The technique, which you experienced, sends a mild current through the brain, which is thought to temporarily alter the likelihood by which neurons in the underlying region's fire. This is achieved by placing two electrodes--one positive (the anode) and one negative (the cathode) on the scalp, and running current across them. In recent years, research has substantiated the possibility that tDCS might temporarily improve motor abilities by putting the anode over specific regions of your brain, including the motor cortex and the dorsolateral prefrontal cortex..

The behavioral consequences of neuronal inhibition associated with cathodal stimulation are less well understood. Based on previous research (Roe et al., 2016), we hypothesized that cathodal stimulation over the dorsolateral prefrontal cortex would temporarily reduce the speed and accuracy by which you performed the motor task involving the pegboard.

In order to test this, we put the anode over your left dorsolateral prefrontal cortex during one of your three visits to the laboratory and reversed the polarity for another visit (by instead placing the cathode over that same region). In the remaining visit, though you may not have been aware of it, the stimulation actually faded out after an initial 30 seconds of stimulation. As such, it is not thought to have meaningful effects on the excitability of the underlying neurons. And because people tend to get used to the sensations associated with tDCS, many participants are unable to distinguish this form of "sham" stimulation from more prolonged stimulation treatments. As such, the sham condition provides a baseline, against which we can compare the effects of anodal and cathodal stimulation of the left dorsolateral prefrontal cortex.

We apologize for not informing you about the nature of the sham condition until now. The aim was to control for any expectations participants might have about the effects of the stimulation technology. Now that you are fully aware of the details of our experiment, may we still use the data that we collected from you?

What if I want to know more?

Please contact the researcher, Zongheng Zhang, at zz2302@bard.edu or his faculty supervisor, Dr. Justin Hulbert (jhulbert@bard.edu), if you have any further questions regarding the study. If you have concerns about your rights as a research participant, please contact the Bard College IRB at irb@bard.edu. Should you experience any health concerns as a student, you are invited to explore Bard College's Student Health Services (<http://www.bard.edu/healthservices/>). And, if you have experienced emotional distress, you are encouraged to contact one of the following: Bard Counseling Center (at 845-758-7433), BRAVE (at 1-845-758-7777) or the National Alliance on Mental Illness's (NAMI's) HelpLine (at 1-800-950-6264). **Thank you again for your participation!**

Appendix I : Left hand result of FTT**Reaction time of FTT in left hand (raw data)**

Anodal tDCS		Cathodal tDCS		Sham tDCS	
346.8	319.5	309.1	306.2	289.1	306.2
282.8	273.0	350.3	321.4	289.8	279.6
413.7	374.6	406.5	334.4	364.5	349.8
420.6	381.0	380.8	366.3	365.2	363.7
421.9	361.3	390.4	347.5	365.3	352.5
372.4	353.3	386.4	356.2	284.9	305.2
384.5	361.0	357.3	326.4	372.9	324.5
377.7	367.6	379.6	356.2	299.8	300.0
369.6	359.7	361.7	362.9	330.1	305.7
382.8	351.9	405.1	366.7	302.6	288.5

Accuracy of FTT in left hand (raw data)

Anodal tDCS		Cathodal tDCS		Sham tDCS	
0.96	0.94	0.93	0.92	1.00	0.99
0.96	0.99	0.99	0.99	0.99	1.00
0.99	0.99	0.99	0.92	0.95	0.99
0.99	0.99	0.97	0.95	0.98	0.97
0.98	0.97	0.96	0.95	0.99	0.99
0.95	0.98	1.00	0.97	0.96	0.98
0.95	0.95	0.97	0.94	0.99	0.97
0.98	0.96	0.96	0.94	0.97	0.96
0.96	0.98	0.99	0.95	0.99	0.96
0.98	0.99	0.99	0.91	0.95	0.98