Exploring the reliability of tDCS:
A registered report

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Abstract

Transcranial direct current stimulation (tDCS), a form of non-invasive brain stimulation, has become an important tool for the study of *in-vivo* brain function due to its modulatory effects. Over the past two decades, interest in the influence of tDCS on behaviour has increased markedly, resulting in a large body of literature spanning multiple domains. However, the effect of tDCS on human performance often varies, bringing into question the reliability of this approach. While reviews and meta-analyses highlight the contributions of methodological inconsistencies and individual differences, no published studies have directly tested the intra-individual reliability of tDCS effects on behaviour. Without an understanding of how reliable tDCS is at eliciting consistent behavioural effects, progress in the area of tDCS research will be limited, as will its potential for application. Here, we present a large scale, pre-registered, double-blind and sham-controlled crossover study, which aims to assess the reliability of two single-session tDCS montages at producing previously replicated behavioural effects in a single cohort of 100 individuals.

Keywords: *tDCS, motor-learning, response-learning, reliability, intra-individual, behaviour*

Introduction

Non-invasive brain stimulation is a powerful neuro-modulatory technique that has been extensively used in research and clinical settings to assess and improve performance on various perceptual, cognitive and motor tasks (Nitsche *et al.,* 2003; Reis *et al.,* 2009; Benninger *et al.,* 2010; Loo *et al.,* 2012; Agarwal *et al.,* 2013; Martin *et al.,* 2014; Filmer *et al.,* 2017b). In addition, it can be employed to investigate brain function and behaviour (Nitsche et al, 2006; Marshall & Binder, 2013). In recent years, the use of a particular form of non-invasive brain stimulation, transcranial direct current stimulation (tDCS), has surged (Filmer, Mattingley & Dux, 2020). This is likely due to several reasons, but its ease of use and low cost make this an attractive method in both pure and applied settings.

tDCS involves a weak electrical current (typically 0.5 – 3mA) being applied to the cortex via electrodes placed on to the scalp. While still a matter of debate, tDCS is generally thought to induce changes in neural excitability, an effect hypothesised to occur via the modulation of neuronal membrane potentials (Bindman, Lippold & Redfearn, 1964; Purpura & McMurtry, 1965; Reinhart *et al.,* 2017). This modulatory effect was traditionally considered to be polarity-dependent, with anodal stimulation increasing cortical excitability and cathodal stimulation decreasing cortical excitability of targeted areas (Nitsche & Paulus, 2000; Nitsche *et al.,* 2007; Pellicciari *et al.,* 2013). However, it is now clear that tDCS effects depend on complex interactions between multiple factors, such as stimulation intensity, duration, polarity, and task-induced neural state (Stagg *et al.*, 2009; Batsikadze *et al.,* 2013; Krause & Cohen Kadosh, 2014; Samani *et al.,* 2019). For example, cathodal tDCS can increase cortical excitability at certain stimulation intensities (Batsikadze *et al.,* 2013), and its effect on measures of long-term depression and long-term potentiation can vary as a direct function of stimulation current and duration (Samani et al, 2019). Further, increasing evidence shows

that the effects of anodal and cathodal tDCS vary substantially across task modalities that involve learning (Filmer *et al.,* 2020b).

Such complexities in the variables that interact to influence tDCS outcomes, including the use of questionable research practices in some studies (Heroux *et al.,* 2017), have led to inconsistent findings in the field. As a result, this has led some to question the efficacy of the approach (Filmer, Dux & Mattingley*,* 2014; Filmer *et al.,* 2020b). In particular, a key issue concerns the intra-subject reliability of tDCS effects on behaviour – i.e. the extent to which tDCS elicits similar effects on behaviour within individuals across different time points. Understanding the reliability of tDCS-related effects on task performance is crucial to validate the large body of experimental tDCS work that has already been undertaken in the area of cognitive neuroscience. Although many meta-analyses have examined the reliability of tDCS effects across different studies (Hoy *et al.,* 2013; Hashemirad *et al.,* 2016; Hill, Fitzgerald & Hoy, 2016; Jamil *et al.,* 2017), to the best of our knowledge, no study has explicitly tested intra-subject reliability of tDCS effects on behaviour. Here, we assess the intra-subject reliability of tDCS by focussing on two (previously replicated) learning paradigms that occur at different levels of information processing (Filmer *et al.,* 2013a, 2019b; Nitsche *et al.,* 2003, Kantak, Mummidisetty & Stinear, 2012).

tDCS in motor learning and cognitive performance

Over the past two decades, many studies have explored the effect of both anodal and cathodal tDCS on learning and training outcomes (for recent reviews, see Dedoncker *et al.*, 2016; Buch *et al.*, 2017; Reinhart *et al.*, 2017; Filmer *et al.*, 2020b). In the first demonstration of tDCS influencing learning, anodal tDCS applied to the primary motor cortex (M1) was shown to improve the learning of movement sequences, as measured on the Serial Reaction Time Task (SRTT; Nitsche *et al.,* 2003). The SRTT is a measure of incidental motor learning and

typically features four stimulus-response pairings presented serially across a large number of trials, with reduced response times to repeated (target) sequences compared to random sequences (Nissen & Bullemer, 1987). In their study, Nitsche and colleagues (2003) found that 1 mA of anodal tDCS applied to the M1 for 15 minutes during the SRTT resulted in faster reaction times during repeated sequences compared to controls. This finding has since been replicated (e.g., Vines, Cerruti & Schlaug, 2008; Kantak, *et al.,* 2012; Cuypers *et al.,* 2013; Karok & Witney, 2013) and has inspired related work investigating effects of M1 tDCS on other forms of motor learning (for a review, see Buch *et al.,* 2017).

Research has also explored the capacity for tDCS to alter cognition. A number of studies show that tDCS applied to the dorsolateral prefrontal cortex (DLPFC) can modulate inhibitory control (Angius *et al.,* 2019), working memory (Fregni *et al.,* 2005; Andrews *et al.,* 2011; Zaehle *et al.,* 2011; Martin *et al.,* 2013), multitasking (Filmer, Mattingley & Dux, 2013; Filmer *et al.*, 2017b) and mind-wandering (Kajimura & Nomura, 2015; Kajimura *et al.,* 2016; Filmer, Griffin & Dux, 2019). For example, our group has repeatedly demonstrated that both cathodal and anodal DLPFC tDCS impacts response selection in a sensory-motor training task that involves learning several stimulus-response pairings. Specifically, we found that 0.7 mA of either cathodal or anodal tDCS for 9 min before the task diminishes the typically observed learning/training-related performance gains (i.e., faster responses) seen in control conditions (Filmer *et al.,* 2013a; Filmer *et al.,* 2019b).

The Present Study

Establishing the reliability of key findings is crucial to the field of cognitive neuroscience. Indeed, at a time when many fields of investigation grapple with a 'replication crisis', and multiple large-scale, multi-lab replication efforts are underway (Klein *et al.,* 2018, 2020), the topic of reliability has never been more relevant to all branches of science. Here

we propose a pre-registered, double-blind and sham-controlled crossover study to assess the intra-individual reliability of two commonly used single-session tDCS protocols that influence learning effects. We first hypothesise that the previously published effects will both be replicated – (H_1) cathodal tDCS to the dlPFC will disrupt training-related performance gains in the response-selection task (Filmer *et al.,* 2013a; 2019b) and (H_2) anodal tDCS to M1 will improve performance in the serial reaction time task (Kantak, *et al.,* 2012). Second, based on neurophysiological (Lopez-Alonso *et al.,* 2015; Jamil *et al.,* 2017) and multi-session studies (Filmer *et al.,* 2017a; 2017b) we hypothesise that these effects of tDCS will be moderately reliable ($p > .60$, $r > .30$) within-individuals across time for both the response-selection task (H_3) and serial reaction time task (H_4). That is to say, for an individual, the difference in their task performance under sham and tDCS conditions will be moderately consistent across time periods.

Methods

Participants

Right-handed participants between 18-35 years of age will be recruited through the student population and community pool at The University of Queensland and will be paid $20AUD per hour that they participate. Handedness will be confirmed using the Edinburgh Handedness Inventory (Oldfield, 1971). A tDCS Safety Screening Questionnaire (see appendix A) will be employed to screen for tDCS contraindications. Specifically, individuals with psychiatric or neurological condition(s), current psychoactive medication use, significant alcohol or drug use, or history of head injuries or concussions will be excluded from participating in the study. In addition, as extensive musical training prevents tDCS improvements on the SRTT (Furuya *et al.,* 2014), individuals with greater than 12 years of musical training will be excluded. To ensure capacity to complete the response selection task,

individuals with deficient colour vision or hearing impairment will also be excluded at pre-screening. Unreported vision/hearing problems will be evident in poor performance in the practice phase, where only participants with accuracy of >60% will be asked to continue in the study. Experimenters and testing procedures will be kept as consistent as possible throughout the study, such that every participant receives the same brief from the experimenters at each stage of testing (see appendix B). The University of Queensland Human Research Ethics Committee has provided approval for this study.

Bayesian Sampling

As per the Bayesian sampling approach, participants will be recruited until strong evidence for the alternative or null hypothesis (i.e., a Bayes factor of $BF_{10} \geq 6$ or $BF_{01} \geq 6$) is achieved for the critical hypothesis test (H_3), or when 100 complete datasets are collected, whichever is sooner. The stopping rule will first be checked once an initial sample of 20 subjects has been achieved, and at every subsequent 5 thereafter. The critical hypothesis test is the correlation between the tDCS effects at time 1 and 2 for the response selection task (see appendix C). We have chosen to use H_3, rather than H_1 or H_2, as both ICC and Bayesian bivariate correlations generally require a larger *N* than simple main effects analysis. Simulations run using the BFDA package in R (Schönbrodt & Stefan, 2018) found that with a weak-moderate correlation (r = 0.4), stopping boundary of $BF_{10} \geq 6$, and maximum sample size of n = 100, 95% of simulations found evidence for the alternative hypothesis. A subsequent *a priori* NHST power analysis conducted in *R* using the *ICC.Sample.Size* package (Rathbone, Shaw & Kumbhare, 2015) found that a sample size of N = 80 would provide adequate power ($1 - \beta = .90$, $\alpha = .02$) to detect an ICC of .40 (p_0= .00) ICC. With respect to the tDCS effects within tasks, the 90% of the simulations run using the BFDA package in R (Schönbrodt & Stefan, 2018) with a small-moderate effect (d = 0.4), stopping boundary of BF_{10}

≥ 6, and a sample size of *n* = 100 found evidence for the alternative hypothesis (i.e., an effect of tDCS). We used a small-moderate effect size (*d* = 0.4) for these simulations as it represents the minimum effect of practical significance and is below the effect sizes of previous studies (Kantak *et al.,* 2012; Filmer *et al.,* 2013a). Thus, we are confident that our sample size of 100 should provide a meaningful amount of evidence for both the correlation and task effect analyses, while also allowing for attrition.

Tasks

Response selection task (*Filmer et al., 2013a*)

Each session of this task requires participants to discriminate between stimuli as quickly and as accurately as possible. Stimuli will be mapped to eight individual keys on a standard QWERTY keyboard, with the task separated into two levels of response load (2 response alternatives vs. 6 response alternatives) that will be interleaved throughout a session in a counterbalanced manner. This task uses two key mappings, with a participant using only one of these versions for all four sessions. To minimise cross session learning, a new set of stimuli will be used for each stimulation session, consisting of coloured circles (red: RGB 237 32 36, dark green: RGB 10 130 65, dark blue: RGB 44 71 151, light green: RGB 109 205 119, light blue: RGB 79 188 220, brown: RGB 167 106 48, pink: RGB 255 57 255, and yellow: RGB 255 235 30), abstract shapes (see Figure 1a), symbols (#, %, @, ~, ˆ, *, +, |) or sounds (eight tones, the same as those used by Dux *et al.,* 2006).

The allocation of stimulus sets to experimental session will be counterbalanced across participants and stimulation type. Participants will complete this task a total of four times, across two weeks. In the first week (T1) participants will complete a sham and active tDCS session separated by a minimum of 24 hours. In the subsequent week (T2) participants will again complete a sham and active tDCS session with stimulation type counterbalanced (see

appendix D). During sessions participants will sit approximately 70 cm from a LCD monitor with a refresh rate of 100 Hz and respond using a standard Macintosh keyboard. A session will begin with an introduction of the stimuli and response keys, followed by two practice blocks of 30 trials for each response load during which accuracy feedback will be provided (Figure 1). Once participants have familiarized themselves with the task, they will complete 540 trials across three phases (180 trials each phase, 90 of each response load) with instructions to respond as rapidly and accurately as possible. Response time will be measured as the time between stimulus onset and keypress, during a response window of 1800 ms following the stimuli presentation. Stimulation will be administered immediately after the first phase, with participants instructed to keep their eyes open and refrain from fidgeting during stimulation. The second phase of training will begin within 1 min of stimulation cessation. The third phase will take place 20 min after the end of stimulation, with participants instructed to sit quietly for the 10 min period between the second and third phases of training. As with Filmer *et al.,* (2013a) response times from the pre-stimulation baseline will be compared to those of the two post-stimulation phases in order to ascertain a measure of performance improvement, with the greatest difference in performance expected between the baseline and 20 min post-tDCS phases.

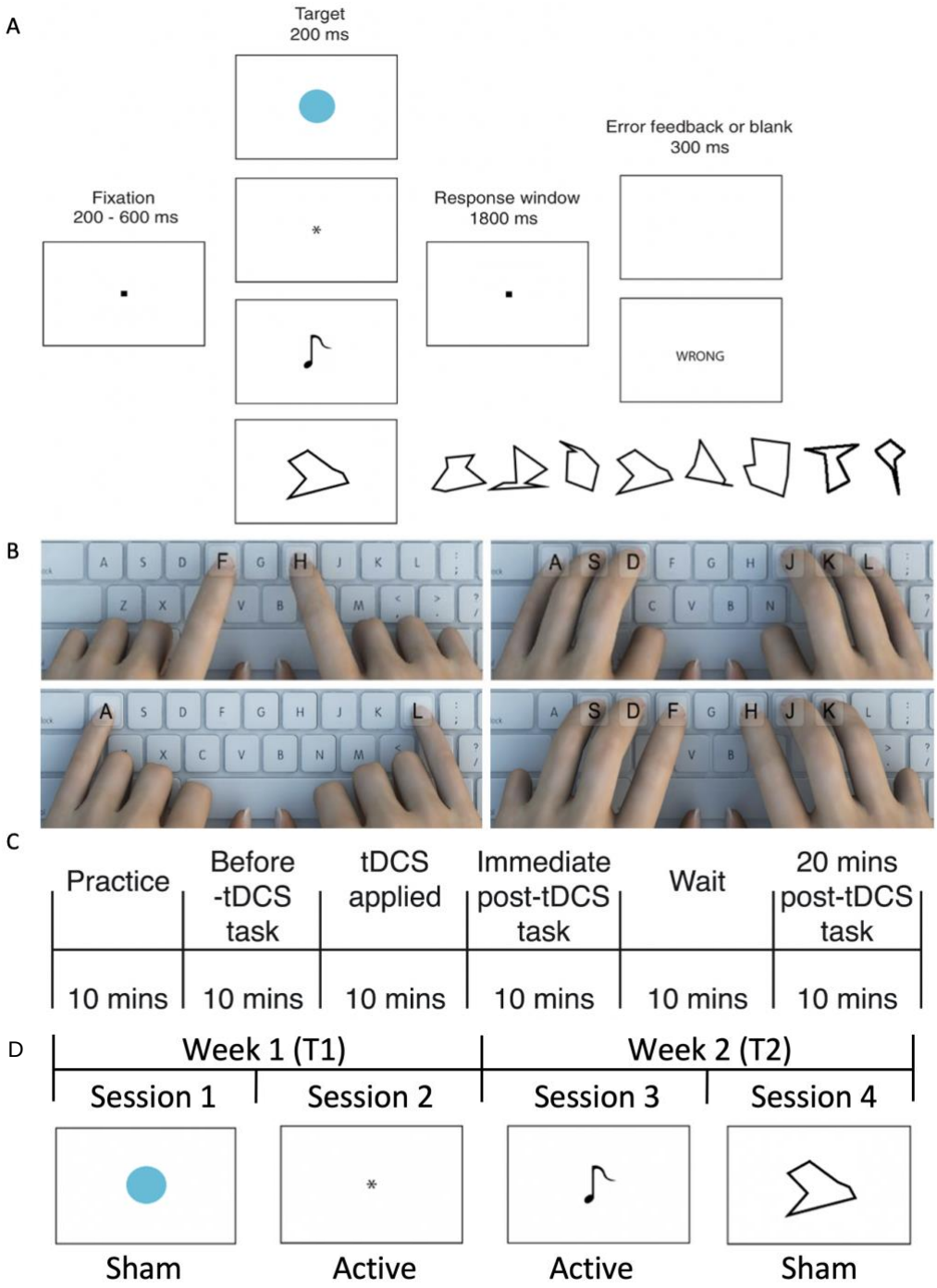

Figure 1. Response Selection Task. (A) An example of a single trial where the participant is presented with one of eight possible target stimuli from one of four stimulus sets and is required to respond with the appropriate key as quickly and as accurately as possible. Error feedback is only given during practice trials. Abstract shape stimulus set shown bottom right. (B) The low-load and high-load response mappings for version 1 and version 2 which are equally distributed throughout a phase. (C) Session schedule. Each of the three task phases consists of 180 trials (90 of each response load). (D) Illustration of full schedule of sessions showing counterbalance of stimuli and stimulation condition. Sessions will be separated by a minimum 24 hours within time periods. Edited from Filmer *et al.,* (2019b).

Serial reaction time task (Nissen & Bullemer, 1987)

We will use a modified SRTT (Kantak *et al.,* 2012), to train the non-dominant hand on four stimuli-response pairings (*A S D F; V B N M; E R T Y; H J K L*), with each finger corresponding to one response key (e.g., *A – little, S – ring, D – middle, F – index*). Consistent with previous studies (Kantak *et al.,* 2012; Karok and Witney, 2013), training the non-dominant hand should increase the magnitude of performance improvements. In each trial of this computer-based task a row of four boxes is presented on screen, three grey and one red target stimulus, with a participant required to respond as rapidly as possible to the stimulus by pressing the appropriate keyboard key (see Figure 2). In each experimental session, participants will be trained on a repeating ten-trial target sequence (e.g., *A-D-S-F-S-A-S-D-A-F*), with a new target sequence used each session in an order which will be counterbalanced across participants. Following a procedure similar to Kantak *et al.,* (2012), each experimental session will begin with 100 trials at baseline (5 target sequences and 5 random sequences), followed by 600 training trials (60 target sequences) while receiving tDCS. Five minutes after the cessation of tDCS, participants will repeat the 100 trial baseline test. Response times will be measured as the time between stimulus onset and keypress. Response times to the trained and random sequences at baseline and end of acquisition will be compared to ascertain a measure of performance improvement. All sessions will be completed using the same equipment and specifications as the previous task. Sessions will also be counterbalanced across two weeks, with a minimum 24 hours between sessions (see appendix D).

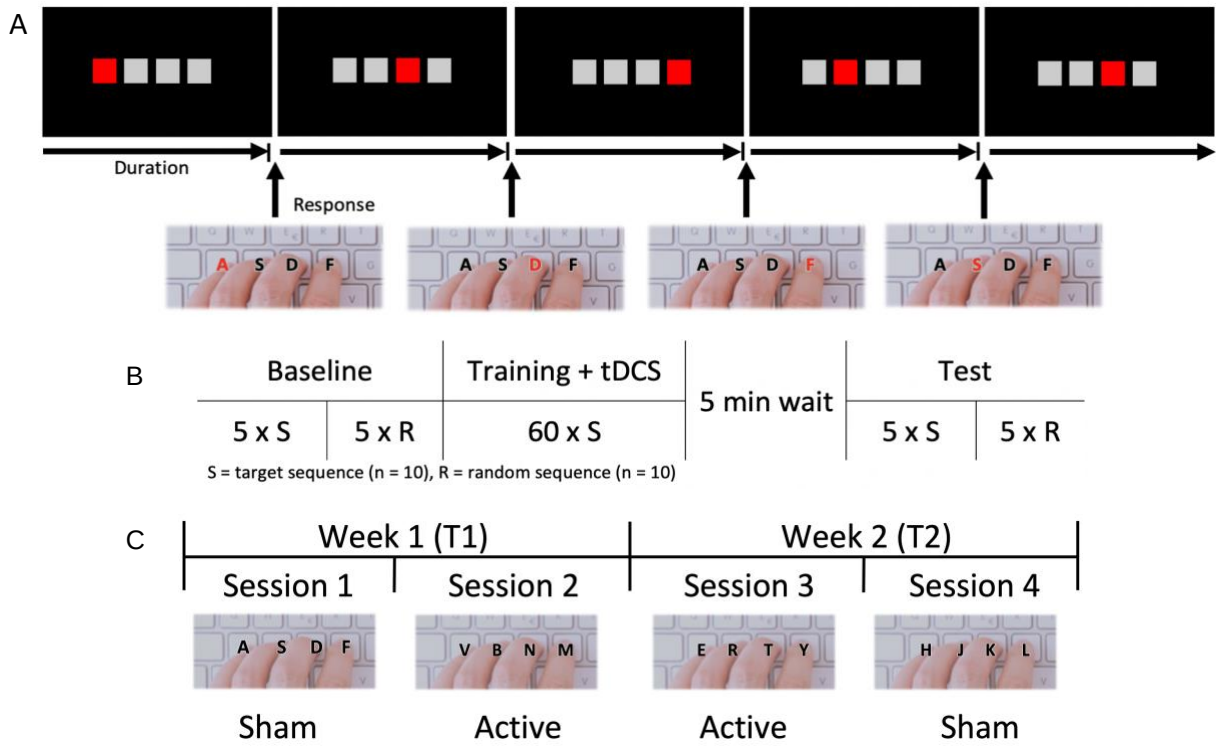

Figure 2. Serial Reaction Time Task. (A) Five consecutive trials shown. Participants are presented with a stimulus and instructed to respond as quickly as possible by pressing the corresponding key. Stimulus remains on screen until response is made. (B) Schedule of session, with 15 min anodal tDCS applied during training. (C) Illustration of full schedule of sessions showing counterbalance of stimuli and stimulation condition. Sessions within a time period will be separated by a minimum 24 hours, and the order of stimulation and stimuli counterbalanced across sessions and time periods.

Stimulation protocols

A Neuroconn DC Plus stimulator (NeuroCare, Germany) will be used to deliver stimulation via two rubber electrodes encased in saline-soaked sponges. The International 10-20 EEG system will be referenced for electrode placement. For the response selection task electrode placement and stimulation parameters will replicate the cathodal condition from Filmer *et al.,* (2013a) with the 25 cm^2 (5 x 5 cm) cathodal electrode placed 1 cm posterior to F_3 (left DLPFC) and the anodal electrode placed over the contralateral supraorbital ridge (Fp_2) in order to deliver 9 min of tDCS (including a 30 sec ramp up/down period) at an intensity of 0.7 mA. We have chosen to only replicate the cathodal condition for this task due to finding it slightly more consistent than the anodal condition during previous iterations (Filmer *et al.,* 2013a, 2019b).

Electrode placement for the SRTT task will replicate Kantak *et al.,* (2012), with an $8cm^2$ (2 x 4 cm) anodal electrode placed on the contralateral M1 (C_4) to the hand being trained, and a $48cm^2$ (6 x 8 cm) cathodal electrode placed on the forehead over the ipsilateral orbit (Fp_1), with tDCS delivered for 15 min (including a 30 sec ramp up/down period) at an intensity of 1 mA. Sham stimulation for all tasks will involve identical electrode placement to the respective active condition, however stimulation will cease after 1.25 min.

The blinding protocol of the NeuroConn tDCS device allows for the programming of stimulation duration, current and frequency. Both active and sham stimulation can be activated by manually inputting a unique numerical code each session, with codes supplied by an experimenter uninvolved in testing. The display of the device will be similar between conditions, with imitation parameters being displayed during sham stimulation. In the event that technical issues affect the duration or intensity of stimulation, or the electrode impedance increases above 15k Ω, that session will be aborted and its data excluded. If practical, aborted sessions will be rescheduled.

Proposed analyses

Overview

The purpose of this study is to assess whether the effects seen in previous research (Nitsche et al., 2003; Kantak et al., 2012; Filmer et al., 2013a; Karok and Witney, 2013) can be reliably reproduced in the same individual over a short time period. The time points being assessed are week 1 and week 2 for both tasks. Raw data files will be immediately uploaded to The University of Queensland Research Data Manager cloud storage as the tasks are completed or lab servers managed by the School of Psychology. Response times (RT) for correct responses will comprise the principal data analysed in both tasks. Analysis will be conducted using JASP software (JASP Team, 2020) and the BFpack package in R (Mulder *et al.,*

2019). Bayesian analyses will use default Cauchy priors centred on 0 with a variance width of 0.707. Although it is normally reasonable to base prior distributions on the posterior distributions of studies one aims to replicate, we have chosen default priors for the following reasons. First, a recent systematic review found that studies without pre-registration, such as those we are replicating, tend to report larger effect sizes compared to those with pre-registration, a discrepancy thought to be due to publication bias (Schäfer & Schwarz, 2019). Basing priors on studies with inflated effect sizes results in larger than necessary distances between the prior distributions, which means in some cases small-medium effects will provide more evidence towards the null than the alternate (Etz & Vandekerckhove, 2016). This issue is further compounded by a number of previous SRTT-tDCS studies not explicitly reporting effect sizes, making it difficult to ascertain average effect sizes across studies. Second, the primary focus of this study is to examine the intra-individual reliability of tDCS effects, regardless of the specific effect size, and thus for these purposes default Cauchy prior distributions are appropriate.

Post-study exclusion criteria

Following completion of the study, individuals who score 2.5 SDs above or below the mean for response time or accuracy, do not follow task instructions, or do not complete all four sessions of a task will have their data excluded from the analysis process. In the instance where an individual's data from only one task is compromised, the data for the second task will still be included, provided it does not meet the above criteria.

Effects of tDCS on response-selection task performance

We expect from previous research that participants will show disrupted performance in the response-selection task when stimulated with cathodal tDCS compared to sham tDCS (Filmer *et al.,* 2013a; 2019b). To test this hypothesis (H_1), Bayesian paired-sample t-tests will

be run on sham and cathodal tDCS RT-change scores (pre-stimulation mean RT – 20 min post-stimulation mean RT) for both T1 and T2 separately. A small-to-medium effect ($d \leq 0.2$) of tDCS, consistent with previous studies (Filmer et al., 2013a; 2019c), is expected. NHST analogues will also be run given this approach is still common in the literature.

Effects of tDCS on SRTT performance

Our analysis of SRTT performance will follow the method of Kantak *et al.,* (2012). For each session mean RT will be calculated from 50-trial blocks of target and random sequences at baseline and the end of acquisition. Training trials will be binned into blocks of 100, with mean RT calculated for each block. Implicit sequence-specific performance will be measured as the difference in mean RT between target and random sequences at baseline and end of acquisition. We will then compare sequence specific performance between conditions (sham vs anodal tDCS) for time period 1 and 2 using Bayesian paired sample t-tests. Our hypothesis (H_2) predicts that anodal tDCS to the contralateral M1 will result in significantly better sequence specific performance at end of acquisition than sham tDCS, as has been observed in several replications previously (Nitsche *et al.,* 2003; Vines *et al.,* 2008; Kantak *et al.,* 2012; Cuypers *et al.,* 2013; Karok & Witney, 2013). Again, NHST analogues will also be run.

Reliability

The intra-individual reliability of tDCS on both task effects across time (cathodal stimulation disrupting response selection task, anodal stimulation enhancing SRTT) will be assessed using intra-class correlation ($ICC_{2,1}$) analysis, a routinely employed technique to assess test-retest reliability. $ICC_{2,1}$, used as an indicator of agreement amongst test sessions is calculated by comparing the variance across different sessions for the same subject with the variance across all sessions and all subjects, and is expressed as;

$$ICC_{2,1} = \frac{MS_B}{MS_B + \frac{(MS_W - MS_E)}{n}}$$

where MS_B is the variance between sessions, MS_W is the variance within sessions and MS_E is variance due to error. The between-condition difference scores from each time period (i.e., T1 active tDCS – T1 sham tDCS) will be used for this correlational analysis, with both Bayesian and NHST bivariate correlations also calculated using the same values. Based on previous neurophysiological studies of tDCS reliability (Lopez-Alonso *et al.,* 2015; Jamil *et al.,* 2017) as well as multi-sessions studies (Filmer *et al.,* 2017a; 2017b), we predict that tDCS effects in both tasks should reach at least moderately reliable thresholds ($p > .60$, $r > .30$) within individuals (H_3, H_4).

Control Analysis

The order of stimulation conditions, tasks, and stimulus sets has been counterbalanced within the study design to control for order effects (see appendix D), thus we have not included any pre-planned control analysis. Stimulation sessions will be separated by a minimum 24 hours.

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Appendix A

Safety Screening Questionnaire

Queensland Brain Institute
School of Psychology
The University of Queensland

Safety Screening Questionnaire for Transcranial Direct Current Stimulation (tDCS)[†]

Full Name:
Date of Birth:

1. Do you have epilepsy or have you ever had a convulsion or a seizure?	❍Yes ❍No
2. Do you know of anyone in your family with epilepsy or a history of seizure?	❍Yes ❍No
3. Have you ever had a fainting spell (or syncope)? If yes, please describe on which occasion(s)? (*please use reverse of form)*	❍Yes ❍No
4. Have you ever had a head trauma that was diagnosed as a concussion or was associated with loss of consciousness?	❍Yes ❍No
5. Have you ever had a brain-related injury, disease or condition (e.g., stroke)?	❍Yes ❍No
6. Do you have any hearing problems or ringing in your ears?	❍Yes ❍No
7. Do you have cochlear implants?	❍Yes ❍No
8. Are you pregnant or is there any chance that you might be?	❍Yes ❍No
9. Do you have metal in the brain, skull or elsewhere in your body (e.g., shrapnel, splinters, fragments from welding or metalwork, surgical clips, etc.)? If so, specify the type of metal (*please use reverse of form).*	❍Yes ❍No
10. Do you have an implanted neurostimulator (e.g., deep brain stimulator, epidural/subdural, vagus nerve stimulator)?	❍Yes ❍No
11. Do you have a cardiac pacemaker or intracardiac lines?	❍Yes ❍No
12. Do you have a medication infusion device?	❍Yes ❍No
13. Are you taking any medications? (*please list on reverse of form*)	❍Yes ❍No
14. Did you ever undergo tDCS in the past? If so, were there any problems.	❍Yes ❍No ❍Yes ❍No
15. Did you ever undergo MRI in the past? If so, were there any problems.	❍Yes ❍No ❍Yes ❍No
16. In the past 24 hours, did you consume alcohol, take any medications, or take any other drugs?	❍Yes ❍No
17. Do you have any skin diseases or use any skin treatments that could potentially cause irritation during tDCS stimulation (e.g., eczema or psoriasis on the scalp)? If yes, please provide details on the overleaf.	❍Yes ❍No

[†]*Rossi et al., 2009. The Safety of TMS Consensus Group. Safety, ethical considerations, and application guidelines for the use of transcranial magnetic stimulation in clinical practice and research. Clinical Neurophysiology, 120:2008–39. Rossi et al., 2011. Screening questionnaire before TMS: An update. Clinical Neurophysiology, 122, 1686.*

I certify that I have understood and honestly answered all question on this document.

Signature: _____ **Date:** _____

Queensland Brain Institute
School of Psychology
The University of Queensland

Question	Response

Appendix B

Verbal Experiment Briefs

The following scripts represent the verbal briefs given to each participant prior to beginning the respective task and session.

Response Selection Task – First Session

"Thank you for participating in our study today. This study is investigating the effect of transcranial direct current stimulation on cognitive and motor task performance.

The task you are about to complete is known as the Response Selection Task. It involves a series of stimuli appearing on the screen which you will then need to select the correct response to by using the appropriate keyboard key. More specific instructions will be provided in the task. It is important that you attempt to complete this task as quickly and accurately as possible. Today is the first of four sessions in which you will complete this task.

During this session you will have a practice period before repeating the task three times, with a 10 min break in between. During the first break you will receive stimulation to your dorsolateral prefrontal cortex. You may feel a slight tingling or itching sensation during stimulation, please advise me if these sensations become too uncomfortable at any stage. Each task repetition takes approximately 10 mins and once today's session should last approximately 70 minutes."

Response Selection Task – Subsequent Sessions

"Thank you for continued participation in our study.

Today you will again complete three repetitions of the Response Selection Task. As before it is important that you attempt to complete this task as quickly and accurately as possible.

As with previous sessions following the first task repetition you will receive stimulation to your dorsolateral prefrontal cortex. You may feel a slight tingling or itching sensation during stimulation, please advise me if these sensations become too uncomfortable at any stage. Again, today's session should last a total of 70 minutes."

Serial Reaction Time Task – First Session

"Thank you for participating in our study today. This study is investigating the effect of transcranial direct current stimulation on cognitive and motor task performance.

The task you are about to complete is known as the Serial Reaction Time Task. It involves a series of stimuli appearing on the screen which you will then need to select the correct response to by using the appropriate keyboard key. More specific instructions will be provided in the task. It is important that you attempt to complete this task as quickly and accurately as possible. Today is the first of four sessions in which you will complete this task.

This session will begin with a short practice period before repeating the task three times, with short breaks in between for you to stretch and take a break. The first repetition is used to get a baseline of your performance and will last approximately 2.5 mins. The second repetition will be the main part of the task, and will last approximately 15 mins. During this second repetition you will receive stimulation to your primary motor cortex. You may feel a slight tingling or itching sensation during stimulation, please advise me if these sensations become too uncomfortable at any stage. The third and final repetition is used to gauge your improvement will again be a short period of 2.5 minutes, completed without any stimulation. Today's session should last approximately 30 minutes."

Serial Reaction Time Task – Subsequent Sessions

"Thank you for continued participation in our study.

Today you will again complete three repetitions of the Serial Reaction Time Task. As before it is important that you attempt to complete this task as quickly and accurately as possible.

As with previous sessions following the first short repetition you will receive stimulation to your primary motor cortex while you complete the main 15 min task repetition. You may feel a slight tingling or itching sensation during stimulation, please advise me if these sensations become too uncomfortable at any stage. You'll then complete another short repetition at the end. Again, today's session should last a total of 30 minutes."

Appendix C

Hypotheses

Table C1. ***Study Design Table***

Question	**Hypothesis**	**Sampling Plan**	**Analysis Plan**	**Interpretation of non-significance**
Does cathodal tDCS to the dlPFC disrupt performance gains in the RST?	H_1: Cathodal tDCS will disrupt performance gains relative to sham as per Filmer *et al.,* (2013a; 2019b).	Continue sampling until BF_{10} >= 6 is met, starting at N = 20. *BFDA* for *d* = 0.4 estimates final N = <100.	Bayesian t-tests comparing performance between active tDCS and sham.	H_0: BF_{10} < 3 will be interpreted as a failure to replicate.
Anodal tDCS to M1 enhances implicit motor learning	H_2: Anodal tDCS will enhance learning, as measured by RT, relative to sham (Nitsche *et al.,* 2003)	Continue sampling until BF_{10} >= 6 is met, starting at N = 20. *BFDA* for *d* = 0.4 estimates final N = <100.	Bayesian t-tests comparing performance between active tDCS and sham.	H_0: BF_{10} < 3 will be interpreted as a failure to replicate.
Is the effect of cathodal tDCS on RST performance reliable within an individual?	H_3: The effect is expected to be moderately reliable across time periods separated by one-week.	Continue sampling until BF_{10} >= 6 is met. *BFDA* for *r* = 0.3 estimates final N =< 100. *ICC.Sample.Size* for p = 0.4, p_0 = 0.0 estimates N > 80 provides 1 - β = .90 at α = .02.	Bayesian Pearson's correlation (JASP) and $ICC_{2,1}$ analysis using the difference scores between sham vs active tDCS for each time period.	H_0: p < 0.4/ r < 0.1 will be interpreted as little to no evidence for reliability. It will not be interpreted as evidence that tDCS behavioural effects are not reliable.
Is the effect of anodal tDCS on SRTT performance reliable within an individual?	H_4: The effect is expected to be moderately reliable across time periods separated by one-week.	Continue sampling until BF_{10} >= 6 is met. *BFDA* for *r* = 0.3 estimates final N =< 100. *ICC.Sample.Size* for p = 0.4, p_0 = 0.0 estimates N > 80 provides 1 - β = .90 at α = .02.	Bayesian Pearson's correlation (JASP) and $ICC_{2,1}$ analysis using the difference scores between sham vs active tDCS for each time period.	H_0: p < 0.4/ r < 0.1 will be interpreted as little to no evidence for reliability. It will not be interpreted as evidence that tDCS behavioural effects are not reliable.

tDCS: transcranial direct current stimulation, dlPFC: dorsal lateral prefrontal cortex, M1: primary motor cortex, RST: Response selection task, SRTT: Serial reaction time task, BFDA: Bayesian Factor Design Analysis (Schonbrodt & Stefan, 2018),

Appendix D

Table D1. *Counterbalanced Schedules*

Week	1 (T1)		2 (T2)		3 (T1)		4 (T2)	
Session*	1	2	3	4	5	6	7	8
A	RST + Sham	RST + tDCS	RST + Sham	RST + tDCS	SRTT+ Sham	SRTT+ tDCS	SRTT+ Sham	SRTT+ tDCS
B	RST + tDCS	RST + Sham	RST + tDCS	RST + Sham	SRTT+ tDCS	SRTT+ Sham	SRTT+ tDCS	SRTT+ Sham
C	RST + Sham	RST + tDCS	RST + tDCS	RST + Sham	SRTT+ Sham	SRTT+ tDCS	SRTT+ tDCS	SRTT+ Sham
D	RST + tDCS	RST + Sham	RST + Sham	RST + tDCS	SRTT+ tDCS	SRTT+ Sham	SRTT+ Sham	SRTT+ tDCS
E	SRTT+ Sham	SRTT+ tDCS	SRTT+ Sham	SRTT+ tDCS	RST + Sham	RST + tDCS	RST + Sham	RST + tDCS
F	SRTT+ tDCS	SRTT+ Sham	SRTT+ tDCS	SRTT+ Sham	RST + tDCS	RST + Sham	RST + tDCS	RST + Sham
G	SRTT+ Sham	SRTT+ tDCS	SRTT+ tDCS	SRTT+ Sham	RST + Sham	RST + tDCS	RST + tDCS	RST + Sham
H	SRTT+ tDCS	SRTT+ Sham	SRTT+ Sham	SRTT+ tDCS	RST + tDCS	RST + Sham	RST + Sham	RST + tDCS

RST: Response selection task, SRTT: Serial reaction time task, tDCS: transcranial direct current stimulation

*All sessions separated by minimum 24 hours.