Enhanced Working Memory Performance via Transcranial Direct Current Stimulation: The
Possibility of Near and Far Transfer

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Abstract

Although working memory (WM) training programs consistently result in improvement on the trained task, benefit is typically short-lived and extends only to tasks very similar to the trained task (i.e., near transfer). It is possible that pairing repeated performance of a WM task with brain stimulation encourages plasticity in brain networks involved in WM task performance, thereby improving the training benefit. In the current study, transcranial direct current stimulation (tDCS) was paired with performance of a WM task (*n*-back). In Experiment 1, participants performed a spatial location-monitoring *n*-back during stimulation, while Experiment 2 used a verbal identity-monitoring *n*-back. In each experiment, participants received either active (2.0 mA) or sham (0.1 mA) stimulation with the anode placed over either the right or the left dorsolateral prefrontal cortex (DLPFC) and the cathode placed extracephalically. In Experiment 1, only participants receiving active stimulation with the anode placed over the right DLPFC showed marginal improvement on the trained spatial *n*-back, which did not extend to a near transfer (verbal *n*-back) or far transfer task (a matrix-reasoning task designed to measure fluid intelligence). In Experiment 2, both left and right anode placements led to improvement, and right DLPFC stimulation resulted in numerical (though not sham-adjusted) improvement on the near transfer (spatial *n*-back) and far transfer (fluid intelligence) task. Results suggest that WM training paired with brain stimulation may result in cognitive enhancement that transfers to performance on other tasks, depending on the combination of training task and tDCS parameters used.

Keywords: working memory; transcranial direct current stimulation; fluid intelligence; transfer; brain stimulation

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Working memory (WM) is a psychological construct used to describe the storage and manipulation of transitory information necessary for complex tasks such as learning and reasoning (Baddeley, 1986; Shah & Miyake, 1999). Performance on WM measures predicts fluid intelligence (Unsworth & Engle, 2007), language comprehension (MacDonald, Just, & Carpenter, 1992), long-term memory and attentional control (Engle & Kane, 2004; Unsworth & Spillers, 2010), mathematics proficiency (DeStefano & LeFevre, 2004), reading comprehension (Daneman & Carpenter, 1980), reasoning ability (Kyllonen & Christal, 1990), and scholastic achievement (Pickering, 2006). Additionally, WM has been implicated in affective processing (Hoffmann, Schmeichel, & Baddeley, 2012) and WM deficits are apparent in a number of psychiatric disorders (Millan et al., 2012). Relevant to both healthy and clinical populations, cognitive training interventions geared toward WM improvement have become popular (Rabipour & Raz, 2012). The goal of such training is to enhance the underlying construct of WM, thereby generalizing performance increases to additional tasks that rely on overlapping cognitive abilities or share neural systems (Dahlin, Neely, Larsson, Backman, & Nyberg, 2008; Owen et al., 2010).

Generalizability of WM performance gains may be divided into near transfer (i.e., to a similar context) and far transfer (i.e., to a dissimilar context; Barnett & Ceci, 2002). Fluid intelligence (Gf) refers to aspects of intelligence involved in encoding and manipulation of novel information, thereby enabling adaptive reasoning and problem solving (Carpenter, Just, & Shell, 1990). Prior research indicates that WM and Gf share between 50% and 60% of their variance (Kane, Hambrick, & Conway, 2005; Gignac, 2014). As Gf relates to academic achievement

(Rohde & Thompson, 2007), it represents a theoretically and practically relevant paradigm by which to examine far transfer in the context of WM training.

While some research supports the notion that WM training is a promising way of increasing Gf (e.g., Jaeggi, Buschkuhl, Jonides, & Perrig, 2008; Jaeggi, Buschkuhl, Shah, & Jonides, 2014; Klingberg, 2010; Perrig, Hollenstein, & Oelhafen, 2009; Sternberg, 2008), other research presents a more cautious view, concluding that WM training programs have limited efficacy regarding improvement of reasoning and general intelligence (e.g., Conway & Getz, 2010; Shipstead, Redick, & Engle, 2012; Sprenger et al., 2013; Chooi & Thompson, 2012; Redick et al., 2013; Thompson et al., 2013; Richmond, Wolk, Chein, & Olson, 2014). Meta-analyses of cognitive training programs designed to enhance WM also advise caution, indicating that while WM training consistently produces near transfer effects, these effects tend to be short-lived and improvement fails to generalize to other domains (Melby-Lervåg & Hulme, 2013; Papp, Walsh, & Snyder, 2009; Valenzuela & Sachdev, 2009; cf. meta-analysis by Au et al., 2014, indicating a small but significant Gf benefit as a result of WM training). Such findings are congruent with a long research history demonstrating that although within-task performance commonly increases with training, transfer to other tasks remains rare (Chase & Ericsson, 1981; Ericsson & Delaney, 1998; Healy, Wohldmann, Sutton, & Bourne, 2006; Singley & Anderson, 1989).

The dorsolateral prefrontal cortex (DLPFC) supports both the maintenance and processing components of WM (Courtney, 2004; Leung, Seelig, & Gore, 2004; Pessoa, Gutierrez, Bandettini, & Ungerleider, 2002), consistent with the idea that processing and memory functions are typically performed by the same neural substrates (Rumelhart et al., 1986).

Due to this involvement in multiple WM components, the DLPFC is an attractive target for neuromodulation in the context of WM training.

Transcranial direct current stimulation (tDCS) is a method of brain stimulation that uses a small electrical current injected through scalp electrodes to modulate neuronal activity (Nitsche & Paulus, 2000). Prior research demonstrates tDCS-induced improvements in cognitive performance for both healthy adults and for those with clinical disorders, on tasks ranging from motor learning to decision making (for reviews, see Coffman, Clark, & Parasuraman, 2014; Dayan et al., 2013; Manenti, Cotelli, Robertson, & Miniussi, 2012). Due to its involvement in WM, the DLPFC has proven a popular target for research investigating the impact of tDCS on WM task performance, often utilizing the *n*-back task (e.g., Andrews, Hoy, Enticott, Daskalakis, & Fitzgerald, 2011; Berryhill & Jones, 2012; Fregni et al., 2005; Ohn et al., 2008; Zaehle, Sandmann, Thorne, Jäncke, & Herrmann, 2011; for reviews, see Berryhill, Peterson, Jones, & Stephens, 2014; Brunoni & Vanderhasselt, 2014).

Prior research suggests an asymmetrical distribution of WM function in younger adults, such that verbal WM tasks are subserved by left frontoparietal regions while visuospatial WM tasks elicit relatively greater right frontoparietal activity (Reuter-Lorenz et al., 2000; Smith & Jonides, 1998; Smith & Jonides, 1999). With respect to the DLPFC, meta-analyses of normative neuroimaging data in the context of WM tasks have been inconclusive, suggesting roughly equal activity in the left and right DLPFC during processing of verbal and spatial stimuli (Nee et al., 2013; Owen, McMillan, Laird, & Bullmore, 2005). Nystrom et al. (2000), assessed brain regions activated by *n*-back tasks using 3 different types of stimuli (letters, abstract shapes, and locations) and found no activation patterns unique to stimuli modality. However, Owen and colleagues (2005) found that when brain activation patterns are compared at the level of identity

versus location monitoring of stimuli, there is relatively greater left-lateralized activity related to verbal as opposed to spatial identity monitoring, while spatial location monitoring (relative to spatial identity monitoring) is more closely associated with right DLPFC activation.

Investigations into the effect of tDCS targeting DLPFC on *n*-back performance have not been comprehensive, as typically only the left, not the right DLPFC is stimulated (e.g., Andrews et al., 2011; Fregni et al., 2005; Gill, Shah-Basak, & Hamilton, 2015; Lally, Nord, Walsh, & Roiser, 2013; Ohn et al., 2008; Teo, Hoy, Daskalakis, & Fitzgerald, 2011; Zaehle et al., 2011). Berryhill and Jones (2012) stimulated either the left or right DLPFC during performance of verbal and visual 2-back tasks, and found both left and right stimulation to be uniformly beneficial to task performance. However, participants were older adults for whom bilateral as opposed to asymmetrical DLPFC activity is typical during WM task performance (Reuter-Lorenz et al., 2000), and only those with relatively high levels of education benefitted from stimulation. It is unknown whether a similar effect would be found in college-age participants.

The current study was designed in light of these conflicting findings regarding asymmetrical functioning of DLPFC and in the context of controversy surrounding transfer effects in WM training. As tDCS-WM paradigms often use the same task to train and evaluate WM function (e.g., Fregni et al., 2005; Ohn et al., 2008; Zaehle et al., 2011), thereby conflating task-specific practice effects with enhanced WM, the current study incorporated a verbal 3-back identity monitoring task, a spatial 3-back location monitoring task, and a Gf task. In Experiment 1, the impact of tDCS on a trained spatial location-monitoring 3-back was evaluated; an untrained verbal identity-monitoring 3-back and an untrained Gf task were used to assess near transfer and far transfer, respectively. In Experiment 2, the impact of tDCS on a trained verbal

identity-monitoring 3-back was evaluated; an untrained spatial location-monitoring 3-back and Gf task were used to assess transfer. In both experiments, participants received stimulation with the anode placed over the left (10-20 EEG electrode site F3) or right (F4) DLPFC.

Experiment 1 – Spatial WM Training

Method

Participants. Thirty-seven participants gave informed consent. One participant was excluded for high scalp impedance. Therefore, 36 participants completed the study. All participants were right-handed, as measured by the Edinburgh handedness inventory (Oldfield, 1971), native English speakers with no history of neurological or psychiatric disorders, head injuries, or vision or hearing problems. None of the participants had surgical or other metal implants in their head, neck, shoulders, or arms, and none reported taking any psychoactive medications at the time of the study. In order to control for stimulation naiveté, participants were excluded if they had previously experienced tDCS. Participants were also excluded for bilingualism which is associated with increased performance on measures of WM (Kroll & Bialystok, 2013; van den Noort, Bosch, & Hugdahl, 2006).

Participants were randomly assigned to stimulation conditions such that 12 received left frontal active stimulation, 12 received right frontal active stimulation, and 12 received sham stimulation. Participants receiving sham stimulation were balanced such that 6 received sham stimulation at site F3 and 6 at site F4. There were no significance differences on any metrics of interest between these two groups, so for analysis purposes the two sham placements were merged to form one sham group consisting of 12 participants. Great effort was made to balance age, gender, handedness, and years of education between groups, and no significant differences were found as determined by individual independent-samples t-tests with $\alpha = 0.05$ (see Table 1).

Immediately prior to stimulation, impedance was measured for each participant (average impedance 43.45 kOhms, SD = 23.56, range 10-79). There was not a significant difference in pre-stimulation impedance between any pair of groups, as determined by individual independent-samples t-tests with $\alpha = 0.05$.

Tasks/Materials. Experimental tasks consisted of a spatial location-monitoring *n*-back task, a verbal identity-monitoring *n*-back task, and an analogical reasoning task based on the Raven's Progressive Matrices task (the Sandia Matrices, Matzen et al., 2010).

In the *n*-back tasks, participants were asked to determine if a stimulus replicated a previously presented stimulus, with a particular lag (in this case, the stimulus that was presented 3 items prior to the current stimulus, setting the value of *n* at 3). An *n* of 3 was selected because prior tDCS studies have found ceiling effects for 1-and 2-back tasks, making the results difficult to interpret (Mulquiney, Hoy, Daskalakis, & Fitzgerald, 2011; Mylius et al., 2012). Stimuli were presented in 24-point Courier New font.

The verbal 3-back task used eight letters as stimuli (B, F, H, K, M, Q, R, and X), which appeared in either upper or lower case on a given trial. This was done to encourage verbal encoding of letter identity as opposed to a visual perceptual mapping between the shapes. Each block consisted of 100 trials: 45 fillers (did not match any of the four previous trials), 35 targets (matched the letter presented 3 trials previously), 10 *n*+1 lures (matched the letter presented four trials previously), and 10 *n*-1 lures (matched the letter presented two trials previously). Each trial was initiated by a 500 ms duration fixation cross, followed by a 500 ms period during which the stimulus appeared directly above the fixation point, and ended with a 1500 ms duration blank screen. The duration of each block was 4.17 minutes. Participants were asked to respond as quickly and accurately as possible, and were given up to two seconds (stimulus presentation

duration + blank screen duration) to respond to each stimulus by pressing keyboard keys that corresponded to “yes” (target) and “no” (non-target).

The structure and duration of the spatial location-monitoring 3-back task was identical to that of the verbal identity-monitoring 3-back with regard to timing and number/distribution of trial types, though the nature of the stimuli differed. An array of eight box outlines (white outline on a black background) was presented around the fixation point. The boxes were arranged in a square shape with two boxes on each side of the fixation point (above, below, left and right). Participants viewed the array of boxes for 500 ms, after which one box was filled in white for 500 ms. Participants were asked to indicate if the location of the filled box matched the location of the filled box from three trials previously. Each WM task block contained the same distribution of stimuli type (i.e., number of targets, fillers, and lures) but stimuli were presented in a different order for each block.

The Sandia Matrices task is based on Raven’s Progressive Matrices (RPM), a measure of Gf in which participants are asked to identify a missing element that completes a pattern (Raven, Court, & Raven, 1998). The Sandia Matrices task expands upon RPM by using similar problem structures to generate a much larger set of matrix problems. These problems have been normed against the Raven’s problems and are of equivalent difficulty (Matzen et al., 2010), and have previously been used to evaluate the impact of brain stimulation on Gf (Santarnecchi et al., 2013). Two sets of matrices were created, containing nine problems each. The matrices in each set had equivalent structures, making the two sets equally difficult. The order in which participants completed the two sets was counterbalanced within each group. For each trial, participants were presented with a 3x3 matrix problem. Participants were given 8 potential solutions to the problem, presented at the bottom of the screen concurrent with the matrix

problem, and were asked to select the most appropriate solution by pressing the keyboard number that corresponded to the solution number (1-8). Participants were given up to 45 seconds to respond to each matrix. Following either a response or expiration of the time limit, the task progressed to the next matrix problem. All tasks were programmed using the E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA).

A sensation questionnaire was used to assess the physical sensations experienced by participants during stimulation. Participants were asked to use an 11-point Likert scale that ranged from 0 (“none”) to 10 (“excessive”) to report their perception with regard to the sensations of tingling, itching, and heat/burning, as in previous tDCS research (Coffman, Trumbo, & Clark, 2012). This questionnaire was administered at three points during stimulation: first at one minute following initiation of stimulation, then again at the five-minute mark, and again at the ten-minute mark. Stimulation was stopped if participants reported a 6 or higher on any scale.

In order to determine if stimulation impacted participant mood, participants were given a mood questionnaire both before and after stimulation. Participants were asked to indicate their level of agreement with nine statements, including “I feel nervous or excited”, “I feel tired or fatigued”, “I feel confused or disoriented”, “I feel sad or down”, “I feel tense or frustrated”, “I feel dizzy or light-headed”, “I feel nauseous”, “I feel physical pain or discomfort”, and “I feel unable to concentrate or pay attention” on a 6-point Likert scale ranging from 0 (“not at all”) to 5 (“very much”). Prior research indicates that tDCS may impact mood and affect (Barrett et al., 2004). While the stimulation parameters used in the current study are somewhat different (e.g., along the dimensions of current strength, stimulation duration, and electrode size), mood data

was collected both as a safety precaution and as a potential metric of interest in the event of post-stimulation changes.

tDCS. Stimulation was delivered using an ActivaTEK ActivaDose II system. In order to avoid bias arising from cephalic placement of electrodes with opposite polarity, an extracephalic placement was used for the reference electrode. The anode was placed either near location F3 or location F4 on the international 10-20 EEG system, above either the left (F3) or right (F4) DLPFC, while the cathode was placed on a fleshy area near the bicep between the elbow and shoulder, on the arm contralateral to the anode placement. Anode placement was determined using the Beam F3 system of electrode placement (Beam, Borckardt, Reeves, & George, 2009), which has been demonstrated to provide a reasonable approximation to MRI-guided targeting of DLPFC (Mir-Moghtadaei et al., 2015).

Current was delivered for thirty minutes at either 0.1 mA (sham) or 2.0 mA (active) via Amrex A102 square sponge electrodes which have a sponge length of 3.3 cm (11 cm^2) and an outer length of 5 cm (25 cm^2). Sponges were saturated with saline (6.25 mL of 150 mM NaCl solution per sponge) and secured to the participant using Coban self-adhering wrap. A current strength of 0.1 mA was chosen as the sham stimulation condition in order to induce physical sensations typically associated with tDCS without stimulating the cortical area beneath the anode. A study modeling electrical current indicates a current strength of less than 0.5 mA at the electrode size used in this experiment has no impact on brain activity in neural tissue 12 mm beneath the surface of the skin (Miranda, Faria, & Hallett, 2009). Participants in our sham group received 20% of this current strength, making it unlikely that the 0.1 mA administered in our sham condition had a meaningful impact on brain function. A current strength of 2.0 mA was

chosen as the active stimulation current strength as prior research shows that 1.0 mA may be an insufficient current strength to benefit WM task performance (Boggio et al., 2006).

A constant-current sham procedure was used because the traditional method of ramping up the current at the initiation of stimulation then ramping it back down (typically after 30 s) may not be an efficacious blinding method as sensations associated with active stimulation persist beyond this 30 s window (Dundas, Thickbroom, & Mastaglia, 2007; Poreisz, Boros, Antal, & Paulus, 2007).

Double-blinding was accomplished via use of a switch box designed to provide active or sham stimulation based on a coded assignment made by a third party, identical to the blinding procedure described in detail elsewhere (Coffman et al., 2012). The blinding and sham methodology used in the current study are identical to methods used effectively in several prior tDCS studies with similar stimulation parameters (Coffman et al., 2012; Falcone, Coffman, Clark, & Parasuraman, 2012). Coding was released to the experimenters upon completion of data collection.

Procedure

Before starting the experiment, participants gave informed consent, were screened for inclusion and exclusion criteria, and provided demographic and handedness information. Participants then completed a mood questionnaire to serve as a pre-stimulation baseline assessment of emotional state and began the experimental tasks, beginning with the far transfer (Gf) baseline task, near transfer (NT) WM baseline task, and trained (TR) WM baseline task (see Figure 1 for structure of the experiment).

First, participants completed one block of the Sandia Matrices (Gf) task, followed by one block of the verbal 3-back and one block of the spatial 3-back. Included in each baseline block was a brief practice session (1 example matrix problem, 10 practice trials for each *n*-back) in which participants received task instructions. Following completion of these baseline tasks, stimulation was initiated. During stimulation, participants periodically reported physical sensations in tandem with completing four blocks of the trained WM task (spatial 3-back). Following cessation of stimulation, participants completed, in order, one block of the trained WM task (spatial 3-back), one block of the near transfer task (verbal 3-back), and one block of the far transfer (Gf). Participants were instructed to respond to stimuli using the hand ipsilateral to the anode (i.e., for anode position F3, participants responded with the left hand; for anode position F4, participants responded with the right hand). This was done to limit the potential for spread of cortical excitability to the motor cortex in the stimulated hemisphere contributing to reaction time (RT) effects, a technique previously implemented in tDCS-WM research targeting the DLPFC (Ohn et al., 2008). This is a particularly salient issue given the findings of a recent meta-analysis indicating that tDCS over the DLPFC reliably improves RTs but not accuracy for *n*-back tasks (Brunoni & Vanderhasselt, 2014).

Experiment 2 – Verbal WM Training

Method

Following completion of Experiment 1, a similar experiment was conducted in order to determine if switching the task performed during stimulation from a spatial location monitoring WM task to a verbal identity monitoring WM task would impact results. Tasks, task structures, tDCS parameters, and experimental procedure were identical to those used in Experiment 1 with a single difference—the verbal 3-back became the trained task performed during stimulation

while the spatial 3-back was used as the near transfer task (see Figure 1). New participants were recruited for the purposes of data analysis.

Participants. Thirty-seven participants gave informed consent. One participant was excluded due to perception of high sensations (tingling > 6) during stimulation. Therefore, 36 participants completed the study. Inclusion and exclusion criteria and group assignment process were identical to those in Experiment 1. No significant differences in age, gender, handedness, or years of education were present between groups, as determined by individual independent-samples t-tests with $\alpha = 0.05$ (Table 1). Following informed consent, participants completed the study in accordance with the procedure described in Experiment 1, with the order of WM task performance reversed. There was not a significant difference in pre-stimulation impedance between any groups, as determined by individual independent-samples t-tests with $\alpha = 0.05$ (average impedance 57.81 kOhms, SD = 19.54, range 18-82).

Data Analysis. To limit the number of comparisons made, the effects of tDCS on measures of accuracy, signal detection (d'), and RT were compared between cognitive tasks separately for each experiment (spatial training and verbal training) and each stimulation target (left or right DLPFC) using split-plot multivariate analysis of covariance (MANCOVA). Standardized change scores were first computed for each subject by dividing the difference from baseline (run 1) by the baseline standard deviation for each of the three cognitive tasks, separately for each group. In order to assess performance changes within the trained WM task (spatial memory in Experiment 1, verbal in Experiment 2), a 2 (active and sham) x 5 (TR run 2-6) MANCOVA was used (henceforth referred to as within-task MANCOVA), where the five TR scores were entered into the model as the within-subjects factors and group designation as the between-subjects factor. We additionally performed exploratory comparisons of standardized change scores for each

1 trained task run to investigate effects of tDCS on training progression (TR run 2-5) and pre-
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 5 versus post-stimulation performance (TR run 6; see Tables 2-5). To assess transfer of
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 8 performance changes to other tasks, a second set of MANCOVAs were used (henceforth referred
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 10 to as across-task MANCOVA), where independent variables comprised tDCS condition (active
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 12 and sham) and task (TR, NT, and Gf). We did not assess signal detection in the across-task
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 15 MANCOVAs because this measure cannot be calculated for the Sandia Matrices task. Gender
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 17 and handedness were included as covariates in both analyses as: (1) Gender is a known factor in
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 19 WM experiments (Speck et al., 2000); (2) Handedness is a known factor in cortical lateralization
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 21 of WM function (Burbaud et al., 1995) and handedness laterality quotient is linearly related to
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 23 laterality of language dominance (Knecht et al., 2000), which itself overlaps with verbal WM
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 25 function (Gruber & Goschke, 2004); (3) Both gender and handedness were correlated with WM
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 27 training performance in this study. Follow-up univariate tests were used to further examine
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 29 significant effects, as appropriate. We also examined the degree to which tDCS-mediated
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 31 improvements on the trained task predicted transfer to the NT and Gf tasks using linear
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 33 regression. Overall model significance and R^2 change were assessed for models separately
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 35 predicting NT and Gf standardized change scores from TR standardized change scores,
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 37 controlling for gender and handedness. Regression models were examined separately for each
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 39 group and training condition.
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48 To assess the degree to which effects reported here were related to physical sensation or
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 50 mood associated with tDCS, mean sensation levels (three measures: itching, heat, and tingling),
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 52 initial mood rating, (nine measures: nervousness, tiredness, confusion, sadness, tenseness,
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 54 dizziness, nausea, pain, and concentration), and change in mood rating (post minus baseline)
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 56 were compared between tDCS groups for each experiment and stimulation target using
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individual independent-samples t-tests. Additionally, relationships between sensations and demographic variables were examined using Pearson correlation in an attempt to characterize parameters that led to physical sensation of tDCS current. These variables included measures of head size (width, length, and circumference), gender, age, handedness, and the ratio of amount of sleep on the previous night to the amount of sleep on a normal night, as sleep deprivation may lead to changes in pain perception (Lautenbacher et al., 2006). Pearson correlation was performed separately for participants receiving active and sham tDCS. As the matrix-reasoning task was self-paced to some extent (maximum of 45 s per trial), we calculated total task duration for each group in order to investigate potential within- or between-group differences in task completion time.

Prior to inferential statistical analysis, the data were checked for outliers and assumptions of univariate analyses were tested. Two outliers existed due to lapse in performance for only one post-tDCS testing data point, with accuracy values of 25% and 2%. These two data points were removed and then interpolated based on baseline performance and participant group. Strong correlation between baseline and post-tDCS scores was confirmed prior to interpolation ($r > 0.8$ in all cases). Data were additionally analyzed with and without these two participants, and no substantive differences were found in results of the two analyses. All variables tested met assumptions of normality (using The Shapiro–Wilk test, $p > 0.01$) and multicollinearity, and pairwise linearity between groups was confirmed by visual assessment of scatterplots. All analyses were performed using IBM SPSS Statistics 21 (IBM, Armonk, NY, US).

Results

Experiment 1: Spatial Working Memory Training

Accuracy for each stimulation group is displayed in Figure 2, and standardized change scores are listed in Table 2 and Table 3. Although there were no main effects or interactions in the omnibus within-task MANCOVA for either stimulation group, there was an interaction between the effects of tDCS and trained (TR), on-stimulation task (spatial *n*-back) run on *d'* for right DLPFC stimulation [Wilks' $\Lambda = 0.55$, $F(4,17) = 3.12$, $p < 0.05$, $\eta_p^2 = 0.42$]. Although there were no significant simple effects (p 's > 0.1) this interaction was driven by greater group differences in *d'* change scores at TR3 and TR5, specifically by an increase in the F4 group, suggesting that tDCS may have had a brief impact on *d'* during training that did not persist after the end of stimulation. Similar TR-run-dependent group differences were observed for accuracy, but these differences also did not achieve statistical significance (Table 3).

There were no significant main effects or interactions in the across-task MANCOVA for Experiment 1 (all $ps > 0.1$), indicating no effects of tDCS, and no significant difference in effects of spatial WM training on performance across the three cognitive tasks (Table 2). To investigate whether the lack of task differences in the across-task MANCOVA were due to null effects of spatial WM training in general, or whether performance for all tasks changed similarly over time, one-sample *t*-tests were used to assess change from baseline in each of the three tasks, collapsing across tDCS groups ($N=36$). Interestingly, significant change from baseline was found only for verbal *n*-back difference scores ($t(35) = 6.02$, $d = 2.03$; $p < 0.001$), suggesting a practice effect for verbal WM, even in the context of spatial WM training, regardless of stimulation. Regression models predicting verbal *n*-back and matrix-reasoning performance from trained, spatial *n*-back performance were not significant for any participant group ($ps > 0.1$).

Experiment 2: Verbal Working Memory Training

Effects of Left Frontal (F3) tDCS

Accuracy for each stimulation group is displayed in Figure 2, and change scores are listed in Table 4. A significant effect of tDCS was found in the omnibus within-task MANCOVA for left frontal tDCS vs. sham [Wilks' $\Lambda = 0.57$, $F(3,18) = 4.51$, $p < 0.05$, $\eta_p^2 = 0.43$], where tDCS differed from sham in standardized accuracy and d' change scores, but not RT change scores, across all TR runs [Accuracy: $F(1,20) = 14.28$, $p < 0.001$, $\eta_p^2 = 0.42$; d' : $F(1,20) = 12.82$, $p < 0.01$, $\eta_p^2 = 0.39$] (Table 4).

In the across-task MANCOVA, a significant interaction was found between tDCS condition and cognitive task [Wilks' $\Lambda = 0.73$, $F(2,19) = 3.52$, $p < 0.05$, $\eta_p^2 = 0.28$] indicating significantly different effects of tDCS during verbal WM training for each of the three cognitive tasks (Table 4). Further investigation of these effects revealed significant differences between active and sham tDCS groups only for the verbal n -back ($F(1,20) = 6.60$, $p < 0.05$), and not the spatial n -back or matrix-reasoning task, indicating enhancement of trained verbal n -back performance with left frontal tDCS, which did not transfer to spatial n -back or matrix-reasoning performance. Interestingly, verbal n -back scores only increased in the active tDCS condition ($t(11) = 4.69$, $d = 2.83$, $p < 0.001$), and not sham ($p > 0.1$), indicating that verbal n -back performance was improved with active current, and not without. Collapsing across sham and active tDCS groups, spatial n -back scores were significantly increased ($t(23) = 3.70$, $d = 1.54$, $p < 0.01$), but matrix-reasoning scores were not ($p > 0.1$).

The regression model predicting NT spatial n -back performance from performance on the trained verbal n -back was significant for sham ($R^2 = 0.84$, $F(3,8) = 6.42$, $p < 0.05$) and active participants ($R^2 = 0.87$, $F(3,8) = 8.01$, $p < 0.01$), but R^2 change was significant only for active participants (R^2 change = 0.64, $F(1,8) = 20.48$, $p < 0.01$), suggesting that the significant R^2 for sham was driven by effects of gender and handedness. Regression models predicting matrix-

reasoning performance from trained verbal n -back performance were not significant for any participant group ($ps > 0.1$).

Effects of Right Frontal (F4) tDCS

Accuracy for each stimulation group are displayed in Figure 2, and change scores are listed in Table 5. A significant effect of tDCS was found in the omnibus within-task MANCOVA right frontal tDCS vs. sham [Wilks' $\Lambda = 0.56$, $F(3,18) = 4.65$, $p < 0.05$, $\eta_p^2 = 0.44$], where active current differed from sham in standardized accuracy and d' change scores, but not RT change scores, across all TR runs [Accuracy: $F(1,20) = 9.26$, $p < 0.01$, $\eta_p^2 = 0.32$; d' : $F(1,20) = 13.83$, $p < 0.001$, $\eta_p^2 = 0.41$] (Table 5).

A significant main effect of tDCS condition was found [$F(1,20) = 4.44$, $p < 0.05$, $\eta_p^2 = 0.18$] indicating an increase in d' scores for participants receiving active stimulation during verbal WM training for each of the three cognitive tasks (Table 5). Although no significant differences in accuracy were present when comparing Active vs. Sham at individual tests (Table 5), accuracy scores were significantly increased from baseline for active tDCS participants for all cognitive tasks (verbal: $t(11) = 2.79$; $\underline{d} = 1.68$, $p < 0.01$; spatial: $t(11) = 5.61$; $\underline{d} = 3.38$, $p < 0.01$; Gf: $t(11) = 2.78$; $\underline{d} = 1.68$, $p < 0.01$). Only spatial WM task performance was significantly increased in sham tDCS participants ($t(11) = 3.27$, $\underline{d} = 1.97$, $p < 0.01$). No effects were found for RT measures ($ps > 0.1$).

For active tDCS participants, the regression model predicting NT spatial n -back performance from performance on the trained verbal n -back was not significant ($ps > 0.1$), but the model predicting matrix-reasoning performance from trained verbal n -back performance reached trend-level significance ($R^2 = 0.74$, $F(3,8) = 6.42$, $p < 0.05$). Additionally, verbal n -back performance accounted for a significant portion of the variance in matrix-reasoning performance

over and above that explained by the control variables (R^2 change = 0.31, $F(1,8) = 5.55$, $p < 0.05$).

Physical Sensation and Mood

Physical sensations, initial mood ratings, and change in mood ratings did not differ significantly between tDCS groups in Experiment 1 or Experiment 2, for either stimulation condition, and physical sensations did not significantly correlate with any performance outcome measures ($ps > 0.05$). This suggests that performance differences between active and sham groups are indicative of neural modulation rather than due to nonspecific arousal effects caused by physical sensations. Sensation during sham tDCS was significantly correlated with handedness and head size measures. These correlation statistics can be found in Table 6.

At the conclusion of the session, participants were asked to indicate which level of stimulation they thought they had received. Options read “0.1 mA (sham),” “2.0 mA (active),” and “I was unable to tell.” In Experiment 1, 18 of 36 participants (11/24 in the active condition, 7/12 in the sham condition) correctly indicated their stimulation condition; accuracy did not differ between groups ($\chi^2(2) = 0.63$, $p > 0.1$). In Experiment 2, 15 of 36 participants (13/24 in the active condition, 2/12 in the sham condition) correctly indicated their stimulation condition and this significantly differed between groups ($\chi^2(2) = 6.88$, $p < 0.05$). Overall, 33/72 participants correctly indicated their stimulation condition. In addition, in order to determine if any groups responded more accurately than chance would predict, chi-square tests comparing each group against a hypothesized null distribution (evenly distributed responses) were conducted. Similar to between-group comparisons, the only group to respond significantly different than chance was the Experiment 2 sham group ($\chi^2(2) = 7.24$, $p < 0.05$), driven by 10 out of 12 participants responding “I was unable to tell.”

Duration of Matrix-Reasoning Task

As the matrix-reasoning task was self-paced (with a 45 s maximum per trial), we examined the total duration of this task for each group in each Experiment (see Table 7). Paired-samples t-tests were calculated in order to see if differences in completion time from pre- to post-stimulation existed within any groups. All groups completed the matrix-reasoning task faster post-stimulation relative to pre-stimulation (all $ps < 0.05$). Independent samples t-tests were run between each pair of groups for each Experiment using change in task duration (Table 7, column 4) as a dependent variable, revealing that although every group completed the task faster following stimulation, the degree of change did not differ between groups (all $ps > .05$). As all groups averaged post-stimulation completion times of under 3 minutes, there was little opportunity for differences in time course of cortical excitability affecting results.

Discussion.

In Experiment 1, participants trained on a spatial WM task and completed a verbal WM task and matrix-reasoning task before and after training. During the trained task, participants received active (2.0 mA) or sham (0.1 mA) stimulation with the anode placed at F3 or F4 and the cathode placed on the contralateral arm. The results of Experiment 1 suggest improvement in performance on a spatial location-monitoring 3-back task for participants who received active relative to sham stimulation with the anode placed over the right DLPFC (hereafter referred to as the F4/spatial group) during training. Although these findings did not reach statistical significance, the active group consistently performed better than the sham group with regard to training increases across training blocks and the difference between the two groups was marginally significant at training blocks 3 and 5. This pattern of results is consistent with the

notion that right DLPFC is involved in spatial location-monitoring WM (Owen et al., 2005) and that tDCS can improve performance on visuospatial WM tasks (Jeon & Han, 2012).

In Experiment 2, participants trained on a verbal WM task and completed a spatial WM task and matrix-reasoning task before and after training. During the trained task, participants received active (2.0 mA) or sham (0.1 mA) stimulation with the anode placed at F3 or F4 and the cathode placed on the contralateral arm. Results indicate a selective improvement of verbal identity-monitoring WM for participants who received active relative to sham stimulation when the anode was placed over left DLPFC, during verbal 3-back performance (hereafter referred to as the F3/verbal group). This supports findings demonstrating left DLPFC is involved in verbal WM (Owen et al., 2005) and that tDCS can improve performance on a verbal WM task when the anode is placed at F3 (Andrews et al., 2011; Fregni et al., 2005; Lally et al., 2013; Ohn et al., 2008; Teo et al., 2011; Zaehle et al., 2011).

When the anode was placed at position F4 during verbal 3-back training (hereafter referred to as the F4/verbal group), participants in the active stimulation group outperformed those in the sham stimulation group not only on the trained task, but also significantly improved on a near transfer task (spatial 3-back), and a far transfer task (matrix-reasoning). Accuracy and d' change scores indicate significant and consistent benefit of active stimulation for both F3 and F4 groups during training blocks (blocks 2-5), suggesting rate of learning and training gains were accelerated with stimulation. Additionally, accuracy change between pre- and post-training tests (blocks 1 and 6 of the trained task) indicates a stimulation benefit for the F3 group, and both the F3 and F4 active stimulation groups demonstrated significantly improved d' scores relative to sham for block 6 vs. block 1, suggesting tDCS potentiated training benefit for these groups.

In both Experiment 1 and Experiment 2, a practice effect was evident for the near transfer WM task (the task that was performed only twice), but not for the trained WM task (the task that was repeated throughout stimulation). For the near transfer task, the active and sham groups both performed better after training, but the two groups did not differ significantly in terms of the magnitude of their performance gains. For the trained WM task, participants in the F4/spatial group in Experiment 1 and the F3/verbal and F4/verbal groups in Experiment 2 showed improvements in performance while the participants receiving sham stimulation did not. The absence of a practice effect for the training WM task in the sham groups suggests behavioral fatigue for repeatedly administered, non-adaptive n-back tasks. The results from the active stimulation groups suggest that active stimulation using particular electrode placements may counteract behavioral fatigue. Active and sham groups did not differ with regard to intensity of physical sensations experienced during stimulation, and sensations did not correlate significantly with performance, suggesting that an explanation of arousal due to physical sensations is not responsible for mitigation of behavioral fatigue in the active groups. Additionally, not all of the active stimulation groups had significant improvements in performance, arguing against a non-specific arousal effect of active stimulation. These results confirm that effects are specific to electrode placement (Boggio et al., 2006; Fregni et al., 2005) and likely due to neuromodulatory effects.

It is worth noting that the F4/verbal group is the only group to demonstrate significantly improved performance from baseline to post-stimulation on the matrix-reasoning task. As all groups performed the self-paced matrix-reasoning task significantly faster following stimulation, this does not appear to be due to a speed-accuracy tradeoff. There are a number of potential explanations for improvement on a Gf measure, including participant motivation, test-taking

strategy, improvement in abilities related to task proficiency (e.g., visuospatial ability), practice effect, and actual increase in Gf.

With regard to motivation, one hypothesis is that improvement on a trained task will motivate participants to perform well on tasks completed following training, resulting in a performance boost in the absence of WM or Gf enhancement, per se (Hayes, Petrov, & Sederberg, 2015). Prior research has indicated that when control groups practice tasks that instill motivation equitable to treatment groups, test scores may improve comparably (Melby-Lervåg & Hulme, 2013; Redick et al., 2013). Thus, motivation transfer may be conflated with transfer due to construct enhancement. Research controlling for motivational factors, however, suggests that in the context of WM transfer to matrix-reasoning task performance motivation is unlikely to account entirely for matrix-reasoning task improvement (Jaeggi et al., 2014). In the current work, three electrode placement/training combinations (F4/spatial, F3/verbal, F4/verbal) resulted in improvement on the trained task, yet in only one instance matrix-reasoning task improvement occurred (F4/verbal). If improvement on a trained task were sufficient to increase participant motivation which then transfers to improvement on untrained tasks (Hayes et al., 2015), we would expect to see task transfer in each instance in which stimulation resulted in improvement on a trained task. As improvement was limited to the trained task in two out of three instances of training improvement, we do not find motivation due to improvement during training to be a compelling explanation for matrix-reasoning task improvement.

Another potential explanation is improvement of visuospatial ability. Prior research using a battery of matrix-reasoning tasks before and after WM training suggests that visuospatial ability rather than matrix-reasoning is improved by the WM training implemented in these studies (Colom et al., 2013; Jaeggi et al., 2014). In the current study, the F4/verbal group

demonstrated task improvement for tasks that involve a strong visuospatial component – a spatial location-monitoring 3-back and a visual matrix-reasoning task – following right DLPFC stimulation, which is associated with improvement in spatial WM (Jeon & Han, 2012). In Experiment 1, however, F4/spatial training resulted in marginal improvement for the active relative to the sham group on the trained task, but this did not transfer to significant improvement on the matrix-reasoning task. If stimulation with the anode over F4 enhanced general visuospatial ability, there should have been an improvement in performance on the matrix-reasoning task, to the extent that matrix-reasoning task performance relies on visuospatial ability.

Another candidate for an explanation of transfer is task strategy. Even in the absence of direct strategy instruction (consistent with the current study) repeated performance of WM tasks is typified by development of strategy use (Holmes, Gathercole, & Dunning, 2009; McNamara & Scott, 2001), and a variety of strategies have been found to improve performance on WM measures (Bengson & Luck, 2015; Turley-Ames & Whitfield, 2003). Therefore, improvement on WM tasks may reflect optimization of existing capacity rather than capacity increase, as repeated task completion promotes strategy development (Holmes et al., 2009). In this study, verbal WM task improvement predicted spatial WM task improvement in the F3/verbal group, although spatial performance enhancement was not significantly different for sham for this group. This suggests that left frontal tDCS may have led to an improvement in WM strategy use here. Similarly, strategy refinement has been found to account for one-third of the variance of score gains on matrix-reasoning problems (Hayes et al., 2015). Transfer of strategy use is thought to occur when tasks share features, thereby enabling an effective strategy developed during performance of one task to enable performance increase on another (Dunning & Holmes, 2014). For transfer between WM tasks, some aspects of task performance are similar between WM and

matrix-reasoning tasks – for instance, determining if the identity of one stimulus matches the identity of another, storing multiple items concurrently in memory – which may explain the shared variance between WM and matrix-reasoning tasks (Gignac, 2014). Thus, transfer of WM training to matrix-reasoning tasks may occur in part due to strategy refinement rather than Gf improvement. Research demonstrating that strategies developed during performance of one WM task transfer to untrained WM tasks (Dunning & Holmes, 2014) supports this idea by demonstrating that tasks that share performance aspects, such as matrix-reasoning and WM tasks (Gignac, 2014), may be amenable to strategy transfer.

While transfer in the current study did not occur for the F4/spatial group, this may be due to task-dependent effects of stimulation such that stimulation during verbal 3-back performance has a different impact than stimulation during spatial 3-back performance. In prior tDCS research targeting left DLPFC, near transfer only occurred when stimulation was applied during performance of a more difficult 3-back task, not when applied during 1-back performance (Gill et al., 2015), demonstrating that task demands during stimulation impact transfer. It is possible that F4/spatial training did not result in transfer because development of a task strategy did not occur under these circumstances, whereas F4/verbal training facilitated activity related to strategy development.

An increase in Gf and strategy refinement are not mutually exclusive explanations. In fact, it has been argued that the ability to both learn and effectively deploy cognitive strategies may be part of Gf (Hayes et al. 2015). The situation is further complicated by research suggesting that higher WM capacity affords the opportunity for strategy development during task performance, particularly when a task or strategy is demanding, such that maintaining task performance during concurrent strategy development and evaluation would require a high WM

capacity (Dunlosky & Kane, 2007; Dunlosky & Thiede, 2004; Turley-Ames & Whitfield, 2003). Therefore, an increase in WM capacity and strategy refinement may overlap. Given the results from Experiment 1, which indicate a selective improvement of spatial WM performance with F4 anode placement, it is also possible that F4 stimulation improves spatial WM independently. Thus, Experiment 2 results for the F4 group may reflect multiple enhancements – strategy refinement associated with verbal WM performance during stimulation, spatial WM near transfer due to carryover effects from recent stimulation over right DLPFC, and matrix-reasoning improvement due to strategy refinement that occurred during verbal WM performance. Indeed, enhancement of verbal WM performance with right frontal tDCS predicted performance enhancement in the matrix-reasoning task, but not the spatial WM task in this study, suggesting that verbal WM and matrix-reasoning improvements were more closely related than verbal and spatial WM improvements. Future work should control for strategy use in order to disentangle the potential contributions of increased WM capacity and strategy use.

The results of the current study suggest that research utilizing a single WM task (e.g., Fregni et al., 2005; Ohn et al., 2008; Zaehle et al., 2011) should be interpreted with caution, as enhancement of WM task performance via tDCS does not guarantee generalization of improvement. The possibility that tDCS-enhanced performance on a WM measure may be task specific undermines the argument that the construct of WM is improved by stimulation when only a single task is administered (e.g., Fregni et al., 2005; Ohn et al., 2008; Zaehle et al., 2011). Performance benefit should occur on other tasks that utilize the same neural substrate (Dahlin et al., 2008), but as the current work demonstrates generalized improvement is not assured. At the very least it may be necessary to qualify improvement as specific to particular aspects or types of WM (e.g., visuospatial WM) when demonstration of transfer is lacking.

Limitations

There are a number of important limitations to the current work that should be addressed in future research. For instance, Gf is typically considered to be the latent variable which explains intercorrelated performance on a variety of tasks, such as analogy making, reasoning, and novel problem solving (Hayes et al., 2015). It has previously been recommended that construct assessment should occur via a battery of multiple tests, which allows for creation of latent variables which avoid task idiosyncrasies driving results (Shipstead et al., 2012). By only using a single measure of Gf, spatial WM, and verbal WM, we were unable to take a latent variable approach for these constructs. Further, although we discuss these results in terms of differences between electrode placements, we were unable to statistically test this comparison (i.e. F3 vs F4 placement) in this study due to insufficient power to detect these effects. In addition, the relatively small group sizes ($n = 12$) may be responsible for the lack of significant findings for certain electrode placement/task combinations (e.g., F4 placement during spatial WM training). Future studies should specifically examine the effect of electrode placement with a larger sample to determine whether any advantage truly exists.

An additional limitation common to standard tDCS research is the lack of focality regarding stimulated brain regions. Frontal areas aside from the DLPFC were likely impacted by stimulation. As the cathode was placed extracephalically (on the arm), these additional regions include not only frontal regions implicated via tDCS research in operations such as inhibition (Ditye, Jacobson, Walsh, & Lavidor, 2012), planning (Dockery, Hueckel-Weng, Birbaumr, & Plewnia, 2009) and risk-taking (Fecteau et al., 2007), but cerebellar and brain stem structures (Bikson, Rahman, & Datta, 2012). The cerebellum has previously been targeted directly in tDCS WM paradigms, with both anodal and cathodal stimulation either impairing task performance

(Boehringer, Macher, Dukart, Villringer, & Pleger, 2012; Ferrucci et al., 2008) or having no effect (van Wessel, Verhage, Holland, Frens, & van der Geest, 2015). In the current work, participants typically benefitted from tDCS; in the one instance in which they did not (F3/spatial training) it was hypothesized that no benefit of tDCS would occur based on PFC asymmetry of function. Therefore, we do not believe cerebellar stimulation played a significant role in the results of the current work. It is still possible, however, that brain regions outside of the frontal cortex are involved in this response.

In the current study, all tasks maintained a static difficulty level rather than implementing an adaptive performance-based difficulty. As the design of both experiments was between rather than within-subjects in nature, non-adaptive tasks allow a comparison between participants that is not confounded with task difficulty (Jones, Stephens, Alam, Bikson, & Berryhill, 2015). Additionally, a recent meta-analysis suggests no difference in performance benefit elicited by adaptive and non-adaptive WM training programs (Karch & Verhaeghen, 2014).

A meta-analysis suggests that single-session tDCS does not reliably benefit any cognitive domain, including WM (Horvath, Forte, & Carter, 2015). While assessment of task transfer is inconclusive in the current work, we did find clear evidence of single-session tDCS task improvement on a WM task performed during stimulation. This is consistent with multi-session tDCS research indicating enhancement of verbal WM performance during training, with near transfer effects evident only when comparing active stimulation to a no-contact control group (Richmond et al., 2014). Similar research has found task transfer effects present only at a 1-month follow-up rather than directly after training (Jones et al., 2015; Martin et al., 2013). Future research should implement a follow-up in order to determine the duration of task improvements as well as evaluate potential sleeper effects. Thus, tDCS may have an additive effect beyond

training alone, or extend the duration of training benefit, but training may serve as the key component. Additionally, while the current study used healthy, young adults as participants, future work may benefit from the inclusion of participants who may respond differently to stimulation-enhanced cognitive training programs, such as older adults (Gutchess, 2014).

Individual differences such as motivation, need for cognition, and implicit theories regarding intelligence may influence training and transfer outcomes (Jaeggi et al., 2014). Physiological characteristics such as head size, shape, skull thickness, subcutaneous fat levels, cerebrospinal fluid density, and topography of the cortical surface may also prove valuable predictors of cognitive training and treatment outcomes that incorporate tDCS (Kim, Kim, Chang, Kim, & Im, 2013; Seibt et al., 2015; Truong et al., 2013). As task strategy offers a potential explanation for the improved matrix-reasoning task performance observed in the current study by the F4/verbal group, future research should track participant strategy, through strategy use interviews tailored to WM tasks (Dunning & Holmes, 2014), independent physiological measures of strategy, such as eye-tracking (Hayes et al., 2015), and use of tasks that encourage or discourage strategy use by manipulating aspects of the task such as presentation rate or semantic links between stimuli (Dunning & Holmes, 2014).

Conclusion

The strong heritability of Gf (Neisser et al., 1996) has led to its conceptualization as a stable trait resistant to interventions in adulthood (Carroll, 1993; Jensen, 1998). Though heritability does not preclude malleability (Dickens & Flynn, 2001), any interventions suggesting alteration of a typically stable construct should be approached skeptically and demand replication and methodological refinement addressing limitations. Prior work pairing 10 stimulation and cognitive training sessions has failed to detect far transfer effects (Jones et al., 2015; Martin et

al., 2013; Richmond et al., 2014), making the single-session improvement on a matrix-reasoning task in the current study somewhat surprising. Type of training, however, may be more important than the training duration (Karchach & Verhaeghen, 2014). If the particular paradigm here is verified as an effective means of improving WM, the shorter duration of training to achieve benefit, the better – in terms of cost, time investment, and participant attrition (Thompson & Foth, 2005). Therefore, while the current study suggests that tDCS paired with WM task performance may improve both WM and Gf under particular circumstances, it is necessary that future work address the above limitations in order to assess the veridicality of the current findings.

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Table 1.

*Participant demographics for Experiments 1 and 2. *Handedness quotient: 100 = right hand dominant, -100 = left hand dominant, 0 = ambidextrous.*

		N	# Males	Age Mean $\pm$ SD	Education Mean $\pm$ SD	Handedness* Mean $\pm$ SD
Experiment 1 – Spatial WM Training						
	Left Frontal tDCS	12	6	18.75 $\pm$ 0.87	13.17 $\pm$ 0.52	76.78 $\pm$ 25.71
	Right Frontal tDCS	12	6	21.42 $\pm$ 5.33	14.04 $\pm$ 0.52	85.05 $\pm$ 17.41
	Sham tDCS	12	6	20.00 $\pm$ 2.09	13.63 $\pm$ 0.52	84.63 $\pm$ 18.23
	Total	36	18	20.06 $\pm$ 3.43	13.61 $\pm$ 0.51	82.15 $\pm$ 20.55
Experiment 2 – Verbal WM Training						
	Left Frontal tDCS	12	6	22.25 $\pm$ 5.76	13.54 $\pm$ 0.51	77.35 $\pm$ 28.37
	Right Frontal tDCS	12	6	18.92 $\pm$ 0.67	12.88 $\pm$ 0.52	68.41 $\pm$ 24.49
	Sham tDCS	12	6	21.50 $\pm$ 6.40	14.17 $\pm$ 0.52	70.31 $\pm$ 30.16
	Total	36	18	20.89 $\pm$ 5.08	13.53 $\pm$ 0.51	72.02 $\pm$ 27.25

Table 2.

Comparisons of standardized change scores between Left Frontal tDCS and sham groups in Experiment 1. TR refers to the trained, on-stimulation task (spatial 3-back), NT refers to the near transfer task (verbal 3-back) and Gf refers to the far transfer matrix-reasoning task.

	Change Scores		Standardized		Stats
	Sham	Active	Sham	Active	
<u>RT (ms)</u>					
TR2 – TR1	-25 ± 18	-59 ± 18	-0.14 ± 0.1	-0.34 ± 0.1	$F(1,20)=1.90; p>0.1$
TR3 – TR1	-84 ± 32	-80 ± 32	-0.48 ± 0.18	-0.46 ± 0.18	$F(1,20)=0.01; p>0.1$
TR4 – TR1	-161 ± 34	-132 ± 34	-0.92 ± 0.19	-0.76 ± 0.19	$F(1,20)=0.37; p>0.1$
TR5 – TR1	-229 ± 42	-129 ± 42	-1.31 ± 0.24	-0.74 ± 0.24	$F(1,20)=2.85; p>0.1$
TR6 – TR1	-215 ± 33	-197 ± 33	-1.23 ± 0.19	-1.13 ± 0.19	$F(1,20)=0.14; p>0.1$
<u>d'</u>					
TR2 – TR1	0.15 ± 0.17	0.25 ± 0.17	0.17 ± 0.19	0.28 ± 0.19	$F(1,20)=0.16; p>0.1$
TR3 – TR1	0.08 ± 0.19	0.13 ± 0.19	0.09 ± 0.22	0.14 ± 0.22	$F(1,20)=0.03; p>0.1$
TR4 – TR1	0.12 ± 0.24	-0.02 ± 0.24	0.13 ± 0.26	-0.02 ± 0.26	$F(1,20)=0.16; p>0.1$
TR5 – TR1	0.06 ± 0.24	-0.14 ± 0.24	0.07 ± 0.27	-0.16 ± 0.27	$F(1,20)=0.36; p>0.1$
TR6 – TR1	0.31 ± 0.26	-0.02 ± 0.26	0.34 ± 0.29	-0.02 ± 0.29	$F(1,20)=0.75; p>0.1$
<u>Accuracy</u>					
TR2 – TR1	1% ± 2%	2% ± 2%	0.11 ± 0.16	0.16 ± 0.16	$F(1,20)=0.06; p>0.1$
TR3 – TR1	0% ± 2%	2% ± 2%	0.04 ± 0.19	0.19 ± 0.19	$F(1,20)=0.34; p>0.1$
TR4 – TR1	0% ± 3%	1% ± 3%	-0.03 ± 0.23	0.05 ± 0.23	$F(1,20)=0.05; p>0.1$
TR5 – TR1	-1% ± 3%	-1% ± 3%	-0.07 ± 0.23	-0.05 ± 0.23	$F(1,20)=0.01; p>0.1$
TR6 – TR1	2% ± 3%	1% ± 3%	0.18 ± 0.24	0.08 ± 0.24	$F(1,20)=0.09; p>0.1$
NT2 – NT1	12% ± 2%	5% ± 2%	1.1 ± 0.21	0.48 ± 0.21	$F(1,20)=4.36; p<0.05$
Gf2 – Gf1	4% ± 5%	5% ± 5%	0.24 ± 0.3	0.32 ± 0.3	$F(1,20)=0.04; p>0.1$

Table 3.

Comparisons of standardized change scores between Right Frontal tDCS and sham groups in Experiment 1. TR refers to the trained, on-stimulation task (spatial 3-back), NT refers to the near transfer task (verbal 3-back) and Gf refers to the far transfer matrix-reasoning task.

	Change Scores		Standardized Change Scores		Stats
	Sham	Active	Sham	Active	
<u>RT (ms)</u>					
TR2 – TR1	-20 ± 21	-76 ± 21	-0.11 ± 0.12	-0.43 ± 0.12	$F(1,20)=3.67; p=0.07$
TR3 – TR1	-85 ± 24	-124 ± 24	-0.49 ± 0.14	-0.71 ± 0.14	$F(1,20)=1.26; p>0.1$
TR4 – TR1	-159 ± 34	-181 ± 34	-0.91 ± 0.19	-1.04 ± 0.19	$F(1,20)=0.21; p>0.1$
TR5 – TR1	-232 ± 32	-208 ± 32	-1.33 ± 0.19	-1.19 ± 0.19	$F(1,20)=0.29; p>0.1$
TR6 – TR1	-214 ± 35	-196 ± 35	-1.22 ± 0.2	-1.12 ± 0.2	$F(1,20)=0.14; p>0.1$
<u>d'</u>					
TR2 – TR1	0.15 ± 0.15	0.24 ± 0.15	0.16 ± 0.17	0.27 ± 0.17	$F(1,20)=0.20; p>0.1$
TR3 – TR1	0.1 ± 0.17	0.5 ± 0.17	0.11 ± 0.19	0.55 ± 0.19	$F(1,20)=2.64; p>0.1$
TR4 – TR1	0.13 ± 0.24	0.31 ± 0.24	0.14 ± 0.27	0.34 ± 0.27	$F(1,20)=0.27; p>0.1$
TR5 – TR1	0.07 ± 0.26	0.68 ± 0.26	0.08 ± 0.29	0.75 ± 0.29	$F(1,20)=2.76; p>0.1$
TR6 – TR1	0.35 ± 0.26	0.27 ± 0.26	0.39 ± 0.29	0.3 ± 0.29	$F(1,20)=0.05; p>0.1$
<u>Accuracy</u>					
TR2 – TR1	1% ± 2%	5% ± 2%	0.11 ± 0.19	0.41 ± 0.19	$F(1,20)=1.34; p>0.1$
TR3 – TR1	1% ± 3%	8% ± 3%	0.07 ± 0.22	0.67 ± 0.22	$F(1,20)=3.83; p=0.06$
TR4 – TR1	0% ± 3%	5% ± 3%	-0.01 ± 0.25	0.45 ± 0.25	$F(1,20)=1.74; p>0.1$
TR5 – TR1	0% ± 3%	8% ± 3%	-0.04 ± 0.28	0.7 ± 0.28	$F(1,20)=3.36; p=0.08$
TR6 – TR1	3% ± 3%	5% ± 3%	0.22 ± 0.26	0.45 ± 0.26	$F(1,20)=0.36; p>0.1$
NT2 – NT1	12% ± 2%	8% ± 2%	1.11 ± 0.21	0.71 ± 0.21	$F(1,20)=1.76; p>0.1$
Gf2 – Gf1	4% ± 5%	7% ± 5%	0.23 ± 0.31	0.45 ± 0.31	$F(1,20)=0.27; p>0.1$

Table 4.

Comparisons of standardized change scores between Left Frontal tDCS and sham groups in Experiment 2. TR refers to the trained, on-stimulation task (verbal 3-back), NT refers to the near transfer task (spatial 3-back) and Gf refers to the far transfer matrix-reasoning task.

	Change Scores		Standardized Change Scores		Stats
	Sham	Active	Sham	Active	
<u>RT (ms)</u>					
TR2 – TR1	-16 ± 23	-15 ± 23	-0.09 ± 0.13	-0.08 ± 0.13	$F(1,20)=0.00; p>0.1$
TR3 – TR1	-68 ± 33	-75 ± 33	-0.38 ± 0.19	-0.42 ± 0.19	$F(1,20)=0.02; p>0.1$
TR4 – TR1	-123 ± 38	-78 ± 38	-0.68 ± 0.21	-0.43 ± 0.21	$F(1,20)=0.70; p>0.1$
TR5 – TR1	-93 ± 43	-112 ± 43	-0.52 ± 0.24	-0.63 ± 0.24	$F(1,20)=0.10; p>0.1$
TR6 – TR1	-131 ± 37	-95 ± 37	-0.73 ± 0.21	-0.53 ± 0.21	$F(1,20)=0.48; p>0.1$
<u>d'</u>					
TR2 – TR1	-0.32 ± 0.16	0.44 ± 0.16	-0.45 ± 0.22	0.62 ± 0.22	$F(1,20)=11.59; p<0.01$
TR3 – TR1	-0.21 ± 0.17	0.38 ± 0.17	-0.29 ± 0.24	0.54 ± 0.24	$F(1,20)=5.72; p<0.05$
TR4 – TR1	-0.33 ± 0.2	0.5 ± 0.2	-0.46 ± 0.28	0.71 ± 0.28	$F(1,20)=8.64; p<0.01$
TR5 – TR1	-0.25 ± 0.22	0.54 ± 0.22	-0.36 ± 0.31	0.76 ± 0.31	$F(1,20)=6.52; p<0.05$
TR6 – TR1	-0.15 ± 0.23	0.75 ± 0.23	-0.22 ± 0.32	1.06 ± 0.32	$F(1,20)=7.72; p<0.05$
<u>Accuracy</u>					
TR2 – TR1	-4% ± 2%	4% ± 2%	-0.44 ± 0.15	0.38 ± 0.15	$F(1,20)=13.66; p<0.001$
TR3 – TR1	-2% ± 2%	5% ± 2%	-0.22 ± 0.21	0.46 ± 0.21	$F(1,20)=5.04; p<0.05$
TR4 – TR1	-4% ± 2%	6% ± 2%	-0.44 ± 0.24	0.55 ± 0.24	$F(1,20)=8.37; p<0.01$
TR5 – TR1	-3% ± 3%	5% ± 3%	-0.34 ± 0.24	0.51 ± 0.24	$F(1,20)=5.90; p<0.05$
TR6 – TR1	1% ± 2%	8% ± 2%	0.14 ± 0.17	0.74 ± 0.17	$F(1,20)=6.24; p<0.05$
NT2 – NT1	8% ± 2%	9% ± 2%	0.85 ± 0.23	0.88 ± 0.23	$F(1,20)=0.01; p>0.1$
Gf2 – Gf1	5% ± 5%	8% ± 5%	0.28 ± 0.25	0.38 ± 0.25	$F(1,20)=0.09; p>0.1$

Table 5.

Comparisons of standardized change scores between Right Frontal tDCS and sham groups in Experiment 2. TR refers to the trained, on-stimulation task (spatial 3-back), NT refers to the near transfer task (verbal 3-back) and Gf refers to the far transfer matrix-reasoning task.

	Change Scores		Standardized Change Scores		Stats
	Sham	Active	Sham	Active	
<u>RT (ms)</u>					
TR2 – TR1	-14 ± 30	-1 ± 30	-0.08 ± 0.17	-0.01 ± 0.17	$F(1,20)=0.09; p>0.1$
TR3 – TR1	-71 ± 36	-60 ± 36	-0.4 ± 0.2	-0.34 ± 0.2	$F(1,20)=0.05; p>0.1$
TR4 – TR1	-127 ± 49	-122 ± 49	-0.71 ± 0.27	-0.68 ± 0.27	$F(1,20)=0.01; p>0.1$
TR5 – TR1	-91 ± 47	-136 ± 47	-0.51 ± 0.26	-0.76 ± 0.26	$F(1,20)=0.45; p>0.1$
TR6 – TR1	-127 ± 38	-167 ± 38	-0.71 ± 0.21	-0.93 ± 0.21	$F(1,20)=0.57; p>0.1$
<u>d'</u>					
TR2 – TR1	-0.32 ± 0.12	0.16 ± 0.12	-0.45 ± 0.17	0.22 ± 0.17	$F(1,20)=7.95; p<0.05$
TR3 – TR1	-0.23 ± 0.15	0.36 ± 0.15	-0.33 ± 0.21	0.51 ± 0.21	$F(1,20)=7.78; p<0.05$
TR4 – TR1	-0.36 ± 0.17	0.19 ± 0.17	-0.5 ± 0.24	0.27 ± 0.24	$F(1,20)=5.19; p<0.05$
TR5 – TR1	-0.26 ± 0.2	0.58 ± 0.2	-0.36 ± 0.28	0.83 ± 0.28	$F(1,20)=9.11; p<0.01$
TR6 – TR1	-0.15 ± 0.22	0.58 ± 0.22	-0.22 ± 0.31	0.82 ± 0.31	$F(1,20)=5.56; p<0.05$
<u>Accuracy</u>					
TR2 – TR1	-4% ± 2%	1% ± 2%	-0.43 ± 0.19	0.14 ± 0.19	$F(1,20)=4.33; p<0.05$
TR3 – TR1	-3% ± 2%	4% ± 2%	-0.25 ± 0.2	0.41 ± 0.2	$F(1,20)=5.24; p<0.05$
TR4 – TR1	-5% ± 3%	3% ± 3%	-0.48 ± 0.27	0.27 ± 0.27	$F(1,20)=3.94; p=0.06$
TR5 – TR1	-4% ± 3%	9% ± 3%	-0.35 ± 0.28	0.85 ± 0.28	$F(1,20)=9.30; p<0.01$
TR6 – TR1	1% ± 3%	8% ± 3%	0.12 ± 0.28	0.75 ± 0.28	$F(1,20)=2.56; p>0.1$
NT2 – NT1	9% ± 2%	14% ± 2%	0.89 ± 0.25	1.4 ± 0.25	$F(1,20)=2.19; p>0.1$
Gf2 – Gf1	4% ± 4%	12% ± 4%	0.23 ± 0.22	0.62 ± 0.22	$F(1,20)=1.55; p>0.1$

Table 6.

*Pearson correlation statistics comparing tDCS sensation and participant demographics for sham tDCS participants. * $p < 0.05$, ** $p < 0.01$.*

	Itching	Heat	Tingling
Itching	1	.144	.546**
Heat	.144	1	.634**
Tingling	.546**	.634**	1
Handedness	-.612**	-.226	-.681**
Sleep Ratio	-.003	-.133	-.281
Extraversion	-.244	-.005	-.192
Head Width	-.582**	-.329	-.425*
Head Length	-.401	-.410*	-.519**
Head Circumference	-.527**	-.307	-.539**
Gender	-.390	-.185	-.315

Table 7.

Average task duration for the self-paced (maximum 45 s/trial) matrix-reasoning task for each group in each experiment. All groups completed the task significantly faster post-stimulation; magnitude of change did not significantly differ between any groups within either experiment.

Group	Average Pre-Stimulation Gf Task Duration (Seconds)	Average Post-Stimulation Gf Task Duration (Seconds)	Change (Post minus Pre)	Statistics (within-group)
Sham (Experiment 1)	180.79 ± 55.38	127.24 ± 34.43	-53.54 ± 33.43	$t(11)=5.55; p<0.01$
F3 (Experiment 1)	169.79 ± 41.06	136.51 ± 21.11	-33.28 ± 35.28	$t(11)=3.27; p<0.01$
F4 (Experiment 1)	208.80 ± 54.68	157.20 ± 36.03	-51.60 ± 41.79	$t(11)=4.28; p<0.01$
Sham (Experiment 2)	176.04 ± 55.37	135.00 ± 37.21	-41.04 ± 42.80	$t(11)=3.32; p<0.01$
F3 (Experiment 2)	177.41 ± 39.98	138.82 ± 36.86	-38.59 ± 43.78	$t(11)=3.05; p<0.05$
F4 (Experiment 2)	165.42 ± 31.43	130.67 ± 43.98	-34.75 ± 41.87	$t(11)=2.88; p<0.05$

Figure Captions

Figure 1. Gf refers to the fluid intelligence task (Sandia Matrices), NT refers to near transfer task (verbal 3-back in Experiment 1, spatial 3-back in Experiment 2), and TR refers to the trained WM task (spatial 3-back in Experiment 1, verbal 3-back in Experiment 2). Run 1 for each task (Gf, NT, TR) was treated as a pre-stimulation baseline.

Figure 2. Mean accuracy for all tasks, groups, and experiments. Results from Experiment 1 are shown in the upper panel, while results from Experiment 2 are shown in the lower panel. Mean accuracy for sham tDCS groups are depicted by blue circles, F3 stimulation groups are depicted by red squares, and F4 stimulation groups are depicted by green triangles. Error bars denote SEM. * $p < 0.05$ (F4 vs Sham). ** $p < 0.01$ (F4 vs sham). # $p < 0.05$ (F3 vs. sham). ## $p < 0.01$ (F3 vs. sham).

Figure 1

Figure 2