THE INVESTIGATION OF DORSOLATERAL PREFRONTAL CORTEX (DLPFC) ACTIVITY IN ITEM AND ASSOCIATIVE MEMORY USING TRANSCRANIAL DIRECT CURRENT STIMULATION (tDCS)

by

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Finally, I dedicate my thesis to my grandparents, Felino and Luz Abellanoza, and Leonor Flores. I hope I continue to make you and the rest of our family proud.

July 29, 2015
Abstract

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Though the dorsolateral prefrontal cortex (DLPFC) has been shown to be important for working and item memory, recent neuroimaging research has suggested that the DLPFC is more important in relational processing for associative memory than initially thought. It has been found that individuals with depressive symptoms often have less activity in the DLPFC; it has also been found that these individuals experience associative memory deficits. However, it remains unclear if associative memory deficits in depression are related to DLPFC activity. Transcranial direct current stimulation (tDCS) can modify cortical excitability and has thus been used in the examination of brain regions and their related functions. The present study used tDCS in individuals with depression to investigate if associative memory deficits were related to DLPFC activity. Only the High Depression group showed a selective enhancement of associative memory after tDCS, whereas the Low Depression group received no benefits from tDCS. The present study suggests that DLPFC activity is related to associative memory deficits in depression. This adds further evidence to the existing body of literature on the DLPFC’s function in associative memory.
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Chapter 1

Introduction

1.1. The Dorsolateral Prefrontal Cortex (DLPFC)

The dorsolateral prefrontal cortex (DLPFC) is an area of the brain that is important in updating and selecting information, as well choosing the subgoals for that information (Fletcher & Henson, 2001). As such, it is an important tool for memory. Its role in working memory is well-documented; these studies use tasks like n-back tasks, which require short-term storage and constant updating for the completion of the task, (for review, see Owen, McMillan, Laird, & Bullmore, 2005), and rehearse/reorder tasks, which require participants either to memorize a list of items or to reorder items based on a certain criterion, like weight or size (Blumenfeld & Ranganath, 2006).

However, some suggest that the DLPFC may specifically be important in working memory processes that influence long-term memory. For example, Blumenfeld and Ranganath (2006) found DLPFC activity correlated with organizational processing that later led to successful long-term memory; further, DLPFC activity particularly supported successful long-term memory of multiple words from the same list, rather than the successful memory of just one or no words. Similarly, Staresina and Davachi (2006) found that the DLPFC engages in higher-level working memory processes that embed information into long-term associative memory networks during encoding. More recently, Ragland et al. (2012) found that relational processing specifically during working memory tasks led to increased DLPFC activation, which then later resulted in more effective associative memory encoding.

Such studies have invigorated the study of the DLPFC with respect to long-term memory. Many questions have been raised regarding whether the DLPFC is more
influential in long-term memory than once thought. Currently, there is a debate on whether the DLPFC is important in general long-term memory processes, or if the DLPFC is recruited specifically for associative memory.

1.1.1. Findings Regarding Role in Long-Term Memory

An early positron emission tomography (PET) study showed that the left DLPFC was involved in the encoding of deeply-processed items rather than shallowly-processed items (Kapur et al., 1994). Functional magnetic resonance (fMRI) imaging studies have corroborated this. Clark and Wagner (2003) found increased left inferior prefrontal activity for the processing of newly-learned items (individually presented pseudo-English words). DLPFC activity specifically supported correct rather than incorrect memory of single, neutral words (Brassen, Weber-Fahr, Sommer, Lehmbeck, & Braus, 2006; Kensinger & Schacter, 2005). Also, Kirwan, Wixted, and Squire (2008) and Hayes, Buchler, Stokes, Kragel, and Cabeza (2011) separately showed that left prefrontal activity supported recollection processes.

Repetitive transcranial magnetic stimulation (rTMS) has also shown the DLPFC’s role in long-term memory. rTMS inhibits memory performance by decreasing cortical excitability. In some studies, rTMS of the DLPFC has resulted in worse episodic memory for items (Floel et al., 2004, Rami et al., 2003; Rossi et al., 2001; Rossi et al., 2006; Turriziani, Smirni, Oliveri, Semenza, & Cipolotti, 2010). Taken together, previous findings suggest that the DLPFC is important in the recognition of individual items.

However, the role of the DLPFC is still unclear regarding the dual-process theory of memory (Mandler, 2008). The dual-process theory differentiates between two types of recognition: recollection and familiarity. Recollection is marked by a resolved sense of memory and can be measured with such responses as high confidence judgments (Yonelinas, Otten, Shaw, & Rugg, 2005) or “Remember” judgments in
“Remember/Know” paradigms (Gardiner, Gregg, & Karayianni, 2006). Familiarity is marked by a vague sense of memory and can be measured with low confidence judgments (Yonelinas, Otten, Shaw, & Rugg, 2005) or “Know” judgments (Gardiner, Gregg, & Karayianni, 2006).

Other studies have found that the DLPFC is more important in familiarity. Wheeler and Buckner (2004) found via fMRI that DLPFC activity related to items for which participants made “Know” judgments. Also, Garoff, Slotnick, and Schacter (2005) found that DLPFC activity did not differentiate between “same” and “similar” stimuli, suggesting that the DLPFC supported more general item encoding. Similarly, Yonelinas, Otten, Shaw, and Rugg (2005) found that while the DLPFC was more active for remembered items than for forgotten items, the DLPFC was also more active for items that were remembered with low confidence rather than high confidence. Duarte, Ranganath, and Knight (2005) found that individuals with DLPFC lesions had impairments in familiarity-based recognition, whereas recollection was affected by neither left nor right frontal lesions.

Some literature has even suggested that DLPFC activity may not be critical for item memory. Studies point to the ventrolateral prefrontal cortex instead as being vital for item memory (Blumenfeld, Parks, Yonelinas, & Ranganath, 2011; Long, Oztekin, & Badre, 2010; Otten, Henson, & Rugg, 2001). Interestingly, Blumenfeld, Lee, and D’Esposito (2014) found that rTMS of the ventrolateral prefrontal cortex, but not the DLPFC, resulted in impaired item memory.

1.1.2. Specific Role in Associative Memory

Rather, a more consistent pattern has been found regarding the DLPFC and associative memory. Another early PET study completed by Kapur et al. (1996) found that encoding of meaningful associations between words recruited activity in the left
DLPFC. More recently, Long, Oztekin, and Badre (2010) showed that DLPFC activity supported relational processing between separately presented items. Also, Hales and Brewer (2011) found DLPFC activity when participants studied pictures individually and then created pairs that participants were tested on later.

Recent neuroimaging studies have directly investigated the DLPFC in associative memory. The DLPFC was shown to be more active during the encoding of item-item relationships, which consistently predicted later successful associative memory (Murray & Ranganath, 2007; Ranganath, 2010). This was corroborated with a recent EEG finding that low frequencies in the left frontal cortex (including the DLPFC) support item-item encoding (Greenberg, Burke, Haque, Kahana, and Zaghloul, 2015).

fMRI data showed the DLPFC to be active during the encoding of new face-name and face-city pairs (Qin, Piekema, Petersson, Han, Luo, & Fernandez, 2007). Prince, Daselaar, and Cabeza (2005) showed that DLPFC activity was present during retrieval (but not encoding) of word pairs. However, Hawco, Armony, and Lepage (2013) found that DLPFC activity is important for learning and recognition of word pairs.

Further, a functional near-infrared spectroscopy (fNIRS) study conducted by Schaeffer, Yennu, Gandy, Tian, Liu, and Park (2014) supported this by showing that oxygenated hemoglobin concentrations were higher in the DLPFC for successful associative memory; the DLPFC was important in both associative encoding and retrieval of word pairs. DLPFC activity has also extended to aurally-presented word pairs, suggesting that the DLPFC is involved regardless of stimulus type (Dolan & Fletcher, 1997; Elmer, Rogenmoser, Kuhnis, & Jancke, 2015; Fletcher, Frith, Grasby, Shallice, Frackowiak, & Dolan, 1995; Shallice, Fletcher, Frith, Grasby, Frackowiak, & Dolan, 1994).
rTMS research has supported this trend. Sandrini, Cappa, Rossi, Rossigni, and Miniassi (2003) found that rTMS of the left DLPFC impaired encoding of unrelated word pairs. Manenti, Cotelli, Calabria, Maioli, & Miniussi (2010) found that when participants engaged in a face-name pair recognition task, those who received rTMS of the left DLPFC had poorer performance during retrieval, suggesting that the left DLPFC is necessary for associative memory retrieval. Further, Hawco, Berlim, and Lepage (2013) found that rTMS of the DLPFC during encoding inhibited memory performance, i.e., decreased memory accuracy in free recall for newly-learned word pairs.

1.2. Depression

The claim that the DLPFC is linked to associative memory function would be strengthened by stimulating the DLPFC in a group that characteristically has less DLPFC activity as well as increased associative memory deficits, then comparing that group’s resulting associative memory performance to that of a healthy group. Those with depression have previously been shown to have decreased prefrontal activation, as well as several episodic memory (particularly associative memory) deficits (Aihara et al., 2007; Austin, Mitchell, & Goodwin, 2001; Brand, Jolles, & Gispen-de Wied, 1992; Mayberg, 2003; Rogers et al., 2004). Thus, a sample of people with higher rates of depressive symptoms would be a valuable group for the study of the DLPFC and associative memory.

Dietsche et al. (2014) found that patients with depression had decreased blood oxygen level dependent (BOLD) responses in the prefrontal cortex during memory tasks. Importantly, Grimm et al. (2008) showed that depression patients have disordered DLPFC activity specifically. Dietsche et al. (2014) reported that, given the prefrontal cortex’s role in choosing, preserving, organizing, and associating information, this
decrease in activity might have been related to the patients’ inability to use effective
cognitive processing methods.

This cognitive ineffectiveness has been illustrated in several associative memory
deficits. Previously, it was shown that depression patients did worse than healthy
counterparts in recalling noun pairs that they encoded by making self-generated,
comparative judgments about the nouns (Roy-Byrne et al., 1986). More recently, they
have been shown to have problems with paired associative learning of nouns
(Michopoulos et al., 2008), as well as the learning, delayed cued-recall, and delayed free-
recall of face-name pairs (Smith, Mullally, McLoughlin, & O’Mara, 2014). These
associative memory deficits may be due to the difficulty of effortful encoding stemming
from a lack of self-generated organizational paradigms used to encode information

Research focusing on this negative correlation between depression and the
ability to handle effortful processes has shown that the amount of associative memory
deficits that people with depression experience is disproportionate to the amount that the
general population experiences (Fairhall, Sharma, Magnusson, & Murphy, 2010; Smith,
Mullally, McLoughlin, & O’Mara, 2014; Werner et al., 2009). These deficits extend to
undiagnosed people; for instance, those with more depressive symptoms (but not
clinically diagnosed with depression) showed the same pattern of impairment in encoding
of words and semantic associates, whereas those in a healthy control group did not show
this pattern (Hasher & Zacks, 1979).

1.3. Transcranial Direct Current Stimulation (tDCS)

Though the depression population experiences these associative memory
deficits, it is still unclear whether DLPFC dysfunction actually causes associative memory
impairments. Thus, stimulating the DLPFC and comparing associative memory accuracy
would help provide evidence of the DLPFC’s specific involvement in associative memory. Transcranial direct current stimulation (tDCS) can be used for this purpose.

TDCS is a form of gentle, noninvasive brain stimulation that introduces low, direct current, which then modulates intracerebral electrical flow (Nitsche et al., 2008). TDCS can modulate cortical excitability, providing a direct manipulation that can link brain area function and memory. In this case, studying how tDCS affects memory accuracy in individuals with depressive symptoms can help elucidate how the DLPFC is important in associative memory.

A schematic of the tDCS setup is presented in Appendix A (Figure A.1). TDCS tonically changes neuronal excitability in one of two ways. First, tDCS can excite neurons by depolarizing resting membrane potentials, leading to more spontaneous cell firing and more activity in the targeted part of the brain. Specifically, anodal stimulation has been shown to increase excitability (Sparing & Mottagh, 2008). Also, tDCS can inhibit neurons by hyperpolarizing resting membrane potentials, leading to less spontaneous cell firing and less activity in the targeted part of the brain. Specifically, cathodal stimulation has been shown to decrease excitability (Sparing & Mottagh, 2008). When one electrode is used for stimulation, the other electrode is used as a reference electrode, or the electrode to which the current will flow.

Changes in excitability produced by tDCS are temporary and depend on current strength, current density, and electrode size (Nitsche et al., 2008). TDCS generates a consistent current strength of up to 2 mA (Sparing & Mottagh, 2008). Current density determines the induced electrical field strength; in humans, larger current densities lead to stronger tDCS effects, and more recent studies typically utilize current densities ranging from .02 to .08 mA/cm² (Nitsche et al., 2008). The size of the electrode also impacts tDCS effects. As electrode size increases, stimulation focality and current
density both decrease; acceptable electrode sizes typically used in study range from 20 to 35 cm$^2$ (Sparing & Mottaghy, 2008).

TDCS has been shown to be reliable, safe, easy to operate, portable, and more cost effective than other forms of stimulation, like TMS (Gandiga, Hummel, & Cohen, 2006; Nitsche et al., 2008). Aside from intracerebellar effects, various types of sensations can arise at the electrode sites during tDCS. Participants of tDCS studies have consistently reported sensations ranging from no sensation at all, to mild tingling/itching/prickling, to slight burning at higher levels of stimulation, all of which are thought to stem from electrochemical reactions created by the transferring of electrons between the electrode and the skin; if the participant experiences any unbearable discomfort or pain, tDCS can easily be turned off (Turi, Ambrus, Ho, Sengupta, Paulus, & Antal, 2014). TDCS has also been shown to be more feasible for double-blind studies, as its interface can provide a true sham session (Gandiga, Hummel, & Cohen, 2006). Compared to other types of noninvasive stimulation, tDCS produces more focal stimulation, and the use of rubber electrodes prevents any electrochemical polarization (Brunoni et al., 2013; Fregni et al., 2005; Nitsche et al., 2008).

Proper placement of the reference electrode is also important, since this is the point to which the current will travel (Clemens, Jung, Mingoia, Weyer, Domahs, & Wilmes, 2014). Typically, the supraorbital area contralateral to the stimulation cite is used as the reference point (Nitsche et al., 2008). Some research has questioned the validity of the use of this area. With the supraorbital area used as the reference point, the tDCS current has the potential to pass through the orbitofrontal cortex during stimulation. An event-related potential (ERP) study showed this area to be implicated in allocating attention to stimuli based on emotion (Hartikainen, Ogawa, & Knight, 2012).
However, research has also supported the use of the contralateral supraorbital area as the reference point. Researchers have found that in healthy subjects, anodal tDCS specifically of the left DLPFC with the reference point on the contralateral supraorbital area did not result in modulation of emotional states (Nitsche, Koschack, Pohlers, Hullemann, Paulus, & Happe, 2012). Others have also argued that turning to extracephalic reference points (e.g., the arm or leg) as an alternative may cause a reduction in stimulation intensity due to the greater distance between electrodes (Moliadze, Antal, & Paulus, 2010). Thus, the use of the right supraorbital area as a reference point is a logical and research-supported method.

Given the ability of tDCS to modulate cortical excitability, tDCS can be used to investigate how cortical function relates to memory performance. In this case, tDCS can be used to investigate how the DLPFC supports associative memory. tDCS-facilitated enhancement of both item and associative memory would suggest that the DLPFC is important in general cognitive control necessary for long-term memory processing overall. However, if anodal stimulation of the DLPFC led to an increase in associative memory accuracy, then it could be said that the DLPFC contributes to associative memory in a specific manner.

1.4 Research Question

Previous literature supports the DLPFC’s specific importance in establishing and retrieving relationships between stimuli. However, the DLPFC’s role in associative memory is still unclear. The biggest impediment is that previous research has largely been correlational in nature. Though aforementioned rTMS studies have shown a possible causal link, they only portray that inhibition of the DLPFC also inhibits associative memory. Also, none of the studies directly compare item memory against
associative memory in conjunction with stimulation. The following study set out to
address these factors.

1.5 Specific Aims

The specific aim of the following study was to establish that the DLPFC is
important in associative memory by showing that an increase in DLPFC activity produced
an increase in associative memory accuracy. The following study utilized tDCS to
modulate cortical excitability. Those with high levels of depressive symptoms were
compared to those with low depression levels. Further, the study directly compared item
and associative memory.

It was assumed that a group who reported low levels of depression symptoms
would gain no benefits from DLPFC tDCS, since they experience no disordered DLPFC
activity. DLPFC tDCS that led to better performance on both item and memory tasks in a
depression group would indicate that the DLPFC is important for cognitive control related
to general long-term memory processing. However, DLPFC tDCS that led to better
performance only on an associative memory task and only for people with high
depression would serve as convincing evidence that the DLPFC is important specifically
for associative memory.

The following study involved a population with different levels of self-reported
depression (High versus Low Depression groups), a noninvasive form of brain stimulation
to modulate DLPFC activity (tDCS versus sham stimulation), and two separate memory
tasks (item versus associative memory). If the High Depression group (but not the Low
Depression group) performed better on the associative memory task after receiving
anodal tDCS, then it could be argued that DLPFC disorder is related to associative
memory impairments.
1.6. Hypotheses

This study examined the relationship between DLPFC activity and associative memory in depression (High Depression versus Low Depression) by stimulating the DLPFC (tDCS versus sham) and comparing performance on item and associative memory tasks. Specifically, it was hypothesized that:

\( H_1 \): Participants would perform better on item memory tasks than associative memory tasks overall.

\( H_2 \): The Low Depression group would perform better on both item and associative memory tasks than the High Depression group.

\( H_3 \): tDCS of the left DLPFC would lead to an improvement in associative memory accuracy for the High Depression group only.

\( H_4 \): tDCS of the left DLPFC would not influence reaction times of memory judgments.
Chapter 2

Methods

This study followed a 2 (High versus Low Depression groups) x 2 (tDCS versus sham stimulation) x 2 (item versus associative memory) design.

2.1. Participants

Seventy-one native English-speaking participants aged 18-40 completed the study in full. They were recruited at the University of Texas at Arlington (UTA) Sona participant pool. Before participating in the study, participants gave informed consent as outlined by the UTA IRB regulatory board. Participants received course credits and study debriefing after their participation. Appendix B, Table B.1 contains information on participant demographics for the present study.

Participants were grouped based on their Center for Epidemiological Studies Depression scale (CES-D) scores (see Appendix B, Table B.2). Those whose scores were one standard deviation above the 16-point clinical cutoff were eligible for the High Depression group, whereas those whose scores fell below one standard deviation of the cutoff were eligible for the Low Depression group (Radloff, 1977; Radloff & Locke, 2000). The Low Depression group scores ranged from 1 to 8; the High Depression group scores ranged from 24 to 53.

Several exclusion criteria were considered for the study. Capping participant age at 40 limited the inclusion of individuals who may show age-related memory declines, which have been shown to start in middle age and to affect relational binding of information in particular (Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000; Naveh-Benjamin, 2000; Park, Kennedy, Rodrigue, Hebrank, & Park, 2013). Since verbal stimuli were used in the study, participants had to be native English language speakers, meaning that they must have learned the language before age 4.
Other exclusion criteria were necessary to abide by safety precautions. Participants could not have been officially diagnosed with or taken medication within the last six months in order to treat the following: depression, anxiety, obsessive-compulsive disorder, attention deficit disorder, any other psychiatric disorder, meningitis, brain tumor, encephalitis, migraines, Parkinson’s disease, Alzheimer’s disease, Tourette’s Syndrome, or any central nervous system illness. Participants also could not have had severe trauma to the head, brain surgery, metal objects implanted in the cranial cavity, pacemakers, medication pumps, or any other implanted electronic hardware. Participants could not have broken or irritated skin on the scalp. Participants could not, within the last six months, have taken any recreational psychoactive drugs (i.e., marijuana, LSD, amphetamines, depressants, or cocaine). Females who were pregnant or were trying to become pregnant could not participate.

2.2. Materials

2.2.1. Stimuli Lists

The words used in the memory tasks were taken from a measure often used in memory studies: the Medical Research Council (MRC) Psycholinguistic Database, a list of over 100,000 words that have been catalogued according to 26 psycholinguistic attributes (Wilson, 1988). The stimuli lists for the present study contained nouns only. The words were matched on the following criteria: Number of Syllables, Number of Letters, Kucera-Francis Word Frequency (K-F-FREQ), Imageability, Concreteness, and Meaningfulness. Chosen nouns had to have 1 to 3 syllables and contain 3 to 9 letters. Nouns also had to have a K-F-FREQ of 5 to 500, an Imageability rating of 4 to 7, a Concreteness rating of 5 to 7, and a Meaningfulness rating of 4 to 7. Further, all words were presented in the same, easily legible font (Arial). Narrowing stimuli according to these factors helped to ensure that the nouns in their written form were familiar enough to
participants so that they could understand and form mental representations of those nouns relatively quickly, yet not odd or distinctive enough to bias participants’ memory (Kucera & Francis, 1967).

2.2.2. tDCS Setup

A battery-powered Neuroimage DC stimulator was used for tDCS. Rubber electrodes (35 cm²) were used to prevent electrochemical polarity. This also addressed criticisms that have argued that the use of smaller electrodes weakens the conclusions of previous tDCS research. These electrodes were placed into sponges (35 cm², red = anode, blue = cathode), which were then soaked in 20 mL of 0.9% NaCl solution to increase conductance of the current (refer back to Figure A.1.). Prior to the start of the experiment, the stimulation settings were saved into the stimulator. In both tDCS and sham sessions, the impedance level was set at 55 kOhms, and the stimulation was set to run for 20 minutes exactly. Also, the current density was set at .08 mA/cm², which is a number within the range used in more recent tDCS research; keeping the current density at this level produces strong effects while curbing current density-related criticisms from earlier research (Wassermann, Epstein, & Ziemann, 2008).

The montage, or electrode placement, used in this study had anode placement on the left DLPFC and cathode (reference) placement on the right supraorbital area. For tDCS sessions, the current strength was set at 2 mA. The stimulation was slowly ramped up over 20 seconds, was kept constant for 20 minutes, and then ramped down over 20 seconds. For sham sessions, the current strength was set as a small, ineffectual current pulse delivered approximately twice per second (every 550 milliseconds); this equates to .11 mA over 0.15 seconds and produced a similar sensation. This kept participants blind to whether the session was a tDCS or sham condition. Also, tDCS and sham codes were
randomized by a research assistant in order to keep the experimenter and participant double-blind to the conditions.

2.3. Procedure

The present study was a double-blind, two-session study (sham vs. tDCS). The intersession interval was 48-72 hours. The study utilized two types of tasks: an item memory task, and an associative memory task. Each task had a study portion and a test portion. The order of sessions (sham vs. tDCS) was counterbalanced across participants.

2.3.1. tDCS Session

Participants individually entered the lab and were given a consent form detailing information on the tDCS procedure, safety precautions, participant confidentiality, voluntary participation, and contact information of the experimenters in the event that participants wished to voice formal comments or concerns. After participants gave informed consent, they gave demographic information. The experimenter ensured that the participants had no hair products in their hair, or makeup on areas that would touch the electrodes. Eligible participants then continued with tDCS, and the experimenter communicated to the participants that if they became uncomfortable or felt pain at any time, they could alert the experimenter and/or elect to stop the experiment with no consequences.

For each participant, the experimenter measured the circumference of the participant’s head with a tape measure. This determined which electroencephalography (EEG) cap (10-20 system) was required in order to locate the left DLPFC. The experimenter fitted the participant with the appropriate EEG cap and then located the F3 node, which has been supported by neuroimaging studies as a reliable method in
locating the left DLPFC (Lafontaine, Theoret, Gosselin, & Lippe, 2013; Lozano & Hallett, 2013). The experimenter marked this area on the participant’s scalp using a water-soluble marker. During this time, the experimenter soaked the sponges in 20 mL of 0.9% NaCl solution to enhance conductance of the current. The anode and cathode were then placed into the sponges and allowed to soak momentarily while the anode and cathode were attached to the stimulator via wires. To overcome any impedance issues, the experimenter used a syringe to add increments of 5 mL to each sponge.

The anode was placed on the mark identifying the left DLPFC; the cathode was placed on the contralateral (right) supraorbital area. Both the anode and cathode were held in place using rubber straps. Anodal tDCS was delivered at 2 mA. Throughout this process, the experimenter gauged participant comfort with verbal communication. The experimenter asked how participants felt at the beginning, halfway through, and toward the end of the tDCS duration. tDCS was stopped if participants reported a score at or above 8, if participants requested to stop, if participants felt discomfort or pain, or in the rare event that participants became ill or unresponsive. Medical attention was not necessary, but the experimenter had resources to seek medical help if participants requested it or seemed to require it.

After stimulation, participants engaged in one item memory task and one associative memory task, presented visually via MATLAB on a desktop computer. Each task had a study portion and a test portion, and participants practiced each study-test run before beginning a study-test cycle. The trials in each task were also randomized and counterbalanced for each session.

The item memory study portion consisted of 200 trials consisting of individual nouns from the aforementioned stimuli list. First, a fixation cross was presented for .5 seconds. Then, nouns were individually presented in the middle of a computer screen for
1.5 seconds. Participants were instructed to read the noun, form a mental representation of the noun, and judge whether that mental representation is “pleasant” or “unpleasant” to them by pressing a corresponding key on the keyboard with their right hand. This task is subjective and was introduced only to ensure that the participant would deeply encode the stimulus. Participants completed these instructions for all 200 nouns.

The item memory test consisted of 300 trials: the 200 studied nouns from study, and 100 new nouns also pulled from the database. A fixation cross was presented for .5 seconds. Then, nouns were presented on the screen one at a time for 1.2 seconds. Participants were instructed to read the noun before determining if it is “old” (i.e., shown during study) or “new” by making a corresponding key press with their left hand. Another fixation cross was then presented for .5 seconds. Then, the question “confidence?” appeared on the screen for 1.2 seconds. During this time, participants used their right hand to press a key corresponding to how confident they were about the old/new decision they made just prior (“7” for low confidence, “8” for middle confidence, and “9” for high confidence).

The associative memory study portion consisted of 90 trials involving noun pairs. First, a fixation cross was presented for .5 seconds. Then, one noun pair was presented in the middle of the screen, with one noun (the “top” noun) above the other noun (the “bottom” noun). The noun pair was visible for 1.5 seconds. During this time, participants were instructed to imagine the nouns and determine if the top noun physically fit into the bottom noun, or if the bottom noun physically fit into the top noun. This task is subjective to how the participants imagined the nouns and was only introduced to ensure that participants actually deeply related the nouns to each other, thus forming an association. Participants pressed corresponding keys to indicate their responses.
The associative memory test involved 135 trials consisting of one of three types of noun pairs: Intact pairs, Rearranged pairs, and New pairs. Intact pairs were nouns from study that remained in the same pairing. Rearranged pairs consisted of nouns from study that were coupled differently. New pairs consisted of nouns not presented during study. First, a fixation cross was presented for .5 seconds. Then, one noun pair was presented for 1.5 seconds. Participants judged if the pair that was presented was Intact, Rearranged, or New by pressing corresponding keys.

2.3.2. Sham Session

The procedure for sham sessions was nearly identical to the tDCS session. The only difference was that instead of 2 mA stimulation, a weak current pulse was delivered approximately twice per second (every 550 milliseconds, or .11 mA over 0.15 seconds). This gave participants a similar sensation to that felt during tDCS and thus kept participants and experimenters blind to the condition.
Chapter 3
Results and Discussion

3.1. Analysis

A 2 (between-subjects variable, group: Low Depression, High Depression) by 2 (within-subjects variable, session: tDCS, sham) by 2 (within-subjects variable, memory type: item, associative) mixed model analysis of variance (ANOVA) of participants’ memory accuracy was run. The corrected recognition score, or $Pr$, was used to measure memory accuracy. $Pr$ has been shown to be more robust against the strength of the association between words and thus more sensitive to memory effects (Feenan & Snodgrass, 1990). $Pr$ is calculated by taking the probability of “hits” (studied stimuli correctly identified as studied) and subtracting “false alarms” (unstudied stimuli incorrectly identified as studied) (Andersen, Morris, Amaral, Bliss, & O’Keefe, 2007; Feenan & Snodgrass, 1990). For item memory, $Pr$ was calculated using the proportions of studied words endorsed as “old” and subtracting new words that were incorrectly endorsed as “old”. For associative memory, $Pr$ was calculated using the proportions of studied intact pairs endorsed as “intact” and subtracting rearranged pairs that were incorrectly endorsed as “intact”. Reaction times (mean of medians) were also collected. Post-hoc $t$-tests were used to probe significant differences and interactions.

3.2. Results

3.2.1. Memory Accuracy ($Pr$)

The first hypothesis ($H_1$) was that participants would perform better on item memory tasks than associative memory tasks. The ANOVA revealed a significant main effect of memory type, $F_{(1,69)} = 281.60, p < .001, \eta_p^2 = .80$. Post-hoc $t$-tests showed that both groups performed better on the item memory task than on the associative memory tasks ($ps < .001$) (refer to Table B.3. or Figure B.4.).
The second hypothesis \((H_2)\) was that the Low Depression group would perform better on both item and associative memory tasks than the High Depression group would. No significant differences were found between the High and Low Depression groups \((p = .69)\) (refer to Table B.3. or Figure B.5.).

The third hypothesis \((H_3)\) was that tDCS of the left DLPFC would lead to an improvement in associative memory accuracy for the High Depression group only. Indeed, there was a significant three-way interaction between group, session, and memory type, \(F_{(1,69)} = 6.50, p = .01, \eta^2_p = .09\). Follow-up t-tests showed that the High Depression group performed significantly better on the associative memory task after tDCS, \(t_{(32)} = 2.08, p < .05\) (refer to Table B.3. or Figures B.6. and B.7.). The Low Depression group showed no such difference \((p = .06)\). There was a marginally significant interaction between group and session, \(F_{(1,69)} = 3.90, p = .05, \eta^2_p = .05\). However, follow-up t-tests showed no significant differences in overall memory performance between Low and High Depression groups during sham sessions, \(t_{(138)} = .42, p = .68\); or during tDCS sessions, \(t_{(140)} = 1.16, p = .25\).

3.2.2. Reaction Times

The fourth hypothesis \((H_4)\) was that tDCS of the left DLPFC would not affect reaction times. The ANOVA revealed a main effect of memory, \(F_{(1,69)} = 293.08, p < .001, \eta^2_p = .81\) (refer to Figure B.3.), indicating that both High and Low depression groups were faster on the item memory task than the associative memory task \((ps < .001)\). No other difference was found in RTs, including no session (tDCS vs. sham) effect.

3.3. Discussion

The results of the present study show that all participants did better on the item memory task than the associative memory task. There were no significant differences between groups across memory tasks. However, a substantial improvement in
associative memory accuracy was found in the High Depression group only after tDCS was administered. These findings lead to several conclusions and prompt directions for future study.

3.3.1. Depression-Related Deficits Not Seen in Item Memory

Overall, the participants performed better on item memory tasks than associative memory tasks. Further, High and Low Depression groups performed similarly well on the item memory tasks, regardless of the tDCS/sham condition. Both groups were also faster at item memory tasks. It is widely accepted that item and associative memory utilize different pathways and structures in the brain (Ranganath, 2010). Item memory may require relatively fewer cognitive resources, since a solitary piece of information is being encoded. In contrast, associative memory may require relatively more attention and effort because multiple pieces of information are being bound and encoded. Studies regarding associative memory deficits support this; attentional or binding processes that are damaged due to things like normal aging, distraction, or other cognitive impairments cause associative memory (versus item memory) to be more susceptible to failure (Troyer, Murphy, Anderson, Hayman-Abello, Craik, & Moscovitch, 2010; Wang, Dew, & Giovanello, 2010).

The results of the present study suggest that depression-related memory deficits are not item-specific. This aligns with research that found no link between DLPFC deactivation and item memory deficits (Blumenfeld, Lee, & D'Esposito, 2014), as well as research that found the ventrolateral prefrontal cortex rather than the DLPFC as being important for item memory (Murray & Ranganath, 2007). Further, Achim and Lepage (2005) suggest that DLPFC activity seen in item retrieval may instead be related to general post-retrieval monitoring processes.

3.3.2. No Difference Between Low and High Depression Groups
There were no differences in memory performance overall between Low and High Depression groups. This could be due to the use of sub-clinical depression participants rather than clinically diagnosed depression patients. The cognitive performance of the sub-clinical group may not be as impaired as in a clinical population.

3.3.3. DLPFC is Related to Associative Memory Deficits

Current research examined if the DLPFC is important for associative memory specifically. Previous fMRI research showed that DLPFC activity was elicited for associative (rather than single item) processing (Blumenfeld, Parks, Yonelinas, & Ranganath, 2010; Dolan & Fletcher, 1997; Fletcher et al., 1995; Hales & Brewer, 2011; Hawco, Armony, & Lepage, 2012; Kapur et al., 1996; Long, Otzekin, and Badre 2010; Murray & Ranganath, 2007; Ranganath, 2010; Schaeffer et al., 2014; Shallice et al., 1994; Qin et al., 2007) and associative retrieval (Prince, Daselaar, & Cabeza, 2005; Schaeffer, Yennu, Gandy, Tian, Liu, & Park, 2014). Research using rTMS (Hawco, Berlim, & Lepage, 2013; Manenti, Cotelli, Calabria, Maioli, & Miniussi, 2010; Sandrini, Cappa, Rossigni, & Miniussi, 2003) has shown that inhibiting the DLPFC led to poorer associative memory performance. The present study adds to the existing body of research by showing that an increase of DLPFC excitability led to an enhancement of associative memory.

The present study did find a marginally significant interaction between group and session, suggesting that perhaps one group benefited from a session while the other did not, or that one group experienced detriments in one session while the other did not. However, post-hoc t-tests showed no differences between Low and High Depression groups based on session alone; instead, this particular interaction may have been driven by the High Depression group’s better performance on the associative memory task after tDCS, reflected in the significant three-way interaction. Further, there was no significant
difference in reaction times between High and Low Depression groups or between tDCS and sham sessions. As such, the most important finding from the present study is the evidence that the DLPFC does play a unique role in associative memory processing rather than just serving as a supportive cognitive resource for overall memory processes.

3.4 Future Directions

Further study, particularly in conjunction with imaging techniques, is necessary to uncover the exact mechanism through which the DLPFC contributes to associative memory. Neuroimaging techniques and study design additions can help address the existing points of debate in the current body of literature. The following are suggestions for future studies examining the DLPFC and associative memory.

3.4.1. DLPFC Connectivity

It has been proposed that the DLPFC’s role in working memory helps in the creation and maintenance of associations between items, as well as the encoding of those relationships into associative networks (Blumenfeld & Ranganath, 2006; Ragland et al., 2012; Staresina & Davachi, 2006). Olson, Jiang, and Moore (2005) found that associative learning facilitated visual working memory tasks. Further study is needed to understand how working memory and associative memory may support each other.

Further, Peña-Gómez and colleagues (2012) found that tDCS of the left DLPFC increased functional network connectivity with focused attentional networks. They also found that stimulation decreased default mode network connectivity. They suggest that cognitive enhancements, like the enhanced memory performance seen in this study, may result from a tDCS-facilitated increase in attentional network synchronicity.

It is also possible that the DLPFC interacts with medial temporal lobe (MTL) structures important for long-term memory. Several studies have shown both DLPFC activity and MTL activity present during associative memory processes. Lateralization of
such activity can differ based on stimulus type. For instance, right DLPFC activity has been shown to support non-verbal processing (Wagner, Poldrack, Eldridge, Desmond, Glover, & Gabrieli, 1998). Right DLPFC activity and left hippocampal/parahippocampal activity were found in associative encoding of pictures (Montaldi et al., 1998).

Contrastingly, it has been suggested that left DLPFC activity, thought to be important for the creation and maintenance of associations between words, may interact with the anterior hippocampus; this structure has been shown to be important in the binding of stimuli necessary for successful associative memory (Jackson & Schacter, 2004; Sperling et al., 2003). Future tDCS studies that also employ imaging techniques can provide evidence of important connections between the DLPFC and other structures important for associative memory processes.

3.4.2. Encoding vs. Retrieval

Future study can also examine whether DLPFC activity is more important during encoding or retrieval. In the present study, tDCS was administered for 20 minutes before the start of the tasks, but these effects may have endured throughout and after the session (for up to 2 hours) (Nitsche et al., 2008). Furthermore, alternating between tasks meant that participants could have completed the associative memory task either at the beginning of the session or toward the end of the session. Though this counterbalanced the tasks across participants, it made it difficult to parse out whether tDCS may have more strongly affected encoding or retrieval, or affected both equally.

The majority of fMRI research has highlighted that DLPFC activity supported successful associative encoding (Blumenfeld, Parks, Yonelinas, & Ranganath, 2011; Blumenfeld & Ranganath, 2006; Kapur et al., 1996, Murray & Ranganath, 2007; Ranganath, 2010, Dolan & Fletcher, 1997, Qin et al., 2007, Fletcher et al., 1995, Shallice et al., 1994). However, DLPFC activity has been shown to be important in associative
retrieval as well (Achim & Lepage, 2005; Bunge, Burrows, & Wagner, 2004; Fletcher & Henson, 2001; Fletcher, Frith, Grasby, Shallice, Frackowiak, & Dolan, 1995; Manenti, Cotelli, Calabria, Maioli, & Miniussi, 2010; Prince, Daselaar, & Cabeza, 2005; Shallice et al., 1994). Recently, Schaeffer, Yennu, Gandy, Tian, Liu, and Park (2014) found that activity in the DLPFC was important in both associative encoding and retrieval.

The present study highlights the DLPFC’s role in associative memory, but it is still unclear whether DLPFC activity is more critical during encoding or retrieval. Further research could examine the rate at which tDCS effects start to diminish, as well as how administering tDCS before encoding versus only before retrieval can affect memory performance. This could then elucidate whether the DLPFC is more important in encoding or retrieval of associative memory.

3.4.3. Clinical Implications

Finally, further research involving patient populations with DLPFC dysfunction-related memory deficits (like depression) would help establish tDCS as a clinical intervention. The present study paradigm could be used in a clinical population to examine associative memory performance. One fMRI study of those with frontotemporal dementia suggested that associative memory impairments may not stem from a decrease in hippocampal volume but mainly from prefrontal cortex dysfunction (Simons, Verfaellie, Galton, Miller, Hodges, & Graham, 2002). Prefrontal cortex tDCS in this population may be able to help assuage associative memory deficits.

Also, Genon, Collette, Feyers, Phillips, Salmon, and Bastin (2013) showed that functional connectivity between the DLPFC and the inferior precuneus was related to successful associative retrieval in healthy controls as compared to patients with Alzheimer's disease. Future research could examine if stimulation could strengthen associative memory by strengthening the functional connectivity between the DLPFC and
the inferior precuneus. Given that tDCS is noninvasive, safe, portable, cost-effective, accessible, and easy to operate, continued research is important for clinical populations.

3.5. Conclusion

In summation, the present data suggests that tDCS of the DLPFC improves associative memory in individuals with depression. This leads to the conclusion that disorders in the DLPFC play a causal role in associative memory deficits. Future directions for this area of study may include studying the specific mechanisms of tDCS; the possible DLPFC-facilitated pathways from working memory to long-term memory; the possible links between the DLPFC, other cortical areas, specific attentional networks, and the MTL; and the specific conditions under which tDCS contributes to memory processes. The present findings not only elucidate the role of the DLPFC in associative memory but also provide foundations for using tDCS as a clinical intervention for memory deficits.
Appendix A

tDCS Setup and Materials
Figure A.1. Schematic of tDCS Setup. (A) Required materials: the Neuroimage DC stimulator (stimulation settings shown), the electrodes and sponges (anode = red, cathode = blue), 0.9% NaCl solution, and EEG 10-20 system cap for DLPFC location. (B) Example of electrode placement. (C) DLPFC Position. Reprinted from “Electrode positioning and montage in transcranial direct current stimulation” by A. F. DaSilva, M. S. Volz, M. Bikson, & F. Fregni, 2011, Journal of Visualized Experiments, 51, e2744, doi: 10.3791/2744. Copyright 2011 by the Creative Commons Attribution License. Reprinted with permission.
Appendix B

Participant Demographics, Memory Tasks, and Study Results
Table B.1. Participant Demographics ($N = 71$)

<table>
<thead>
<tr>
<th>Demographic</th>
<th>Type</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethnicity</td>
<td>Asian</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Black/African American</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Hispanic/Latino</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Multiracial/Other</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>White/Caucasian</td>
<td>25</td>
</tr>
<tr>
<td>Gender</td>
<td>Male</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>35</td>
</tr>
</tbody>
</table>
Table B.2. Participant CES-D Scores. This table contains the mean scores on the Center for Epidemiological Studies Depression (CES-D) Scale for both High and Low Depression groups.

<table>
<thead>
<tr>
<th>Group</th>
<th>n</th>
<th>Score</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Depression</td>
<td>33</td>
<td>30.85</td>
<td>8.44</td>
</tr>
<tr>
<td>Low Depression</td>
<td>38</td>
<td>5.24</td>
<td>1.89</td>
</tr>
</tbody>
</table>

*Note: “SD” = standard deviation.*
Figure B.1. Item Memory Task. This figure illustrates the study and test portions used in the item memory task. During study, participants were instructed to read the word on the screen and rate the word as either "pleasant" or "unpleasant"; this ensured proper deep encoding of the stimulus. During test, participants were instructed to respond if displayed words were old (studied) or new; when the word "confidence?" appeared on the screen, participants were instructed to respond if they had Low, Middle, or High confidence in their old/new decision by pressing corresponding keys.
Figure B.2. Associative Memory Task. This figure illustrates the study and test portions used in the associative memory task. During study, participants were instructed to respond if the top object would physically fit into the bottom object, or vice versa, by pressing corresponding keys. During test, participants were instructed to respond if the displayed pairs were Intact (same as during study), Rearranged (both words seen during study but paired differently), or New (neither word in the pair was seen during study).
Figure B.3. Reaction Times. This figure illustrates faster reaction times (in milliseconds) for item memory tasks. Hatched bars represent the sham condition; solid bars represent the tDCS condition. *** denotes $p < .001$. 
Table B.3. Means and Standard Deviations for Memory Performance – Pr.

<table>
<thead>
<tr>
<th>Group</th>
<th>Item Memory Performance</th>
<th>Associative Memory Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Depression</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sham</td>
<td>.62 (.23)</td>
<td>Sham: .33 (.23)</td>
</tr>
<tr>
<td>tDCS</td>
<td>.64 (.22)</td>
<td>tDCS: .26 (.18)</td>
</tr>
<tr>
<td>High Depression</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sham</td>
<td>.63 (.19)</td>
<td>Sham: .28 (.20)</td>
</tr>
<tr>
<td>tDCS</td>
<td>.64 (.17)</td>
<td>tDCS: .35 (.19)*</td>
</tr>
</tbody>
</table>

*Notes: standard deviations in parentheses; * denotes \( p < .05 \).
Figure B.4. Item vs. Associative Memory Performance. This figure illustrates that all participants performed better on item memory tasks than associative memory tasks. *** denotes \( p < .001 \).
Figure B.5. Low Depression vs. High Depression. This figure illustrates that there were no significant differences between groups on memory performance.
Figure B.6. Item Memory Performance. This illustrates no difference between sham and tDCS sessions for Low Depression or High Depression group.
Figure B.7. Associative Memory Performance. This illustrates a selective enhancement of associative memory in the High Depression group only after tDCS.

* denotes $p < .05$. 
References


stimulation evidenced by resting-state functional MRI. *Brain Stimulation, 5*(3), 252-263.


Biographical Information

Cheryl received her Bachelor of Science degree in Psychology from Texas Christian University in 2010. She received her Master of Arts degree in Clinical Counseling from The Chicago School of Professional Psychology in 2012. She received her Master of Science degree in Experimental Psychology (Health/Neuroscience track) from the University of Texas at Arlington in 2015. As part of Dr. Heekyeong Park’s Cognitive Neuroscience of Memory Lab, Cheryl has published papers examining how stimulus content and object processing affect source memory, comparing associative and source recognition, and investigating how source memory is formed despite distraction.