NON-INVASIVE BRAIN STIMULATION AND THE ENHANCEMENT OF WORKING MEMORY

by

Mark J. Stern, B.A.

A thesis submitted to the Graduate Council of
Texas State University in partial fulfillment
of the requirements for the degree of
Master of Arts
with a Major in Psychological Research
August 2020

Committee Members:

Rebecca Deason, Chair

Logan Trujillo, Co-Chair

Carmen Westerberg

FAIR USE AND AUTHOR’S PERMISSION STATEMENT

Fair Use

This work is protected by the Copyright Laws of the United States (Public Law 94-553, section 107). Consistent with fair use as defined in the Copyright Laws, brief quotations from this material are allowed with proper acknowledgement. Use of this material for financial gain without the author’s express written permission is not allowed.

Duplication Permission

As the copyright holder of this work I, Mark J. Stern, authorize duplication of this work, in whole or in part, for educational or scholarly purposes only.

ACKNOWLEDGEMENTS

I would first like to thank my committee chair, Dr. Rebecca Deason, and co-chair, Dr. Logan Trujillo, for their knowledge, patience, and mentorship during the development of this project. I would also like to thank Dr. Carmen Westerberg, my third committee member, for providing input on the project when asked.

I would also like to thank the members of the Memory and Cognition lab for supporting me during my thesis data collection, especially: Alyse Finch, Kristen Hardin-Sigler, Kaitlyn Fleming, Daniel Reinhuber, Kara Broussard, and Karla Reyes-Fierros, This project would have not gotten nearly the amount of data it did without their hard work and superior time commitment.

Finally, I would like to thank my graduate cohort. Without their support through the master's program, through the best and hardest times, I would have not succeeded nor enjoyed the process. I sincerely thank everyone mentioned above and those who were not but supported me during this time.

TABLE OF CONTENTS

Page

CHAPTER

LIST OF TABLES

LIST OF FIGURES

Figure **Page**

LIST OF ABBREVIATIONS

Abbreviation **Description**

DLPFC – Dorso-Lateral-Prefrontal Cortex

Gold-MSI – Goldsmiths Musical Sophistical Index

IFG – Inferior Frontal Gyrus

LTM – Long-Term Memory

SMG – Supramarginal Gyrus

tACS – Transcranial Alternating Current Stimulation

tDCS – Transcranial Direct Current Stimulation

tPCS – Transcranial Pulsed Current Stimulation

tRNS – Transcranial Random Noise Stimulation

WM – Working Memory

ABSTRACT

Memory is an essential cognitive process that is crucial for day to day tasks. Specifically, working memory allows for the processing and manipulation of information. Baddeley and Hitch's (1974) model of working memory (WM) has been widely accepted and is the basis for many working memory studies. However, this parsimonious model is limited, especially in its ability to distinguish between verbal and tonal information. Furthermore, another debated area of cognitive research is the use of transcranial current stimulation, specifically transcranial direct current stimulation (tDCS), as a cognition enhancer. The present study seeks to address three questions: (1) is there a separate working memory system for music distinct from verbal working memory, (2) in the context of verbal and musical working memory, can tDCS be used to enhance one or both of these types of memory, and (3) can tDCS be used to enhance musical and/or verbal long-term memory, and (4) is there a difference in long-term memory (LTM) confidence judgements between verbal and musical working memory. Participants (*N* = 72) completed a verbal 2-back task, a tonal 2-back task, and an LTM test in which memory for stimuli presented in the WM tasks was tested and confidence was assessed. Participants were randomly assigned to three tDCS conditions: no stimulation, sham, or stimulation. Stimulation occurred for twenty minutes over the left supramarginal gyrus and then participants completed both WM tasks and a LTM assessment. This study failed to find enhancing effects of tDCS on WM or LTM performance when compared to control conditions. Verbal WM task accuracy was higher than the musical WM task, musical LTM was higher than verbal LTM. Participants were more confident on musical stimuli judgments compared to verbal stimuli in the LTM test. This study found mixed results on tDCS's effect on memory.

I. INTRODUCTION

Non-invasive brain stimulation is a somewhat contentious topic in cognitive psychology research. It refers to the application of constant low-intensity current to the skull that partially penetrates through the skull to either excite or inhibit neuronal activity (Moreno-Durante et al., 2014). Devices that perform non-invasive brain stimulation are commonly used to enhance an aspect of cognition, such as memory. Research on the effects of non-invasive brain stimulation has been divided; some studies support the case that non-invasive brain stimulation affects cognition, where others have found no effect. Thus, the further exploration of this technique is imperative. One specific area of interest is the effect this technique has on a person's memory. It is possible that non-invasive brain stimulation may enhance a person's memory, such as by expanding it or increasing the speed, and thus should be explored.

One of the most important features of a person's mental capacity is the ability to form, manipulate, and recall memories. While this seemingly trivial process may not seem to require much effort, this complex memory system should not be taken for granted. However, are we using the full potential of our memory system? While it may not be possible to fully enhance our complex memory system, it may be possible to enhance one specific aspect of it. Several models of memory, as will be discussed later in this introduction, suggest that memory is not a unitary system and is comprised of many components. Thus, it may be possible to improve one of the processes while others remain unaffected. As with other cognitive abilities, the potential of improvement should be studied as it may benefit those with diminished ability, such as in older adults or patient populations.

This review will first cover the general model of memory with specific attention to working memory. Second, this review will cover the basics of non-invasive brain stimulation, the controversy surrounding it with attention to the divided literature, and the implications of future research. As memory is an important process that can be diminished due to age or disease, such as Alzheimer's disease, it is important to explore potential interventions to reverse or prevent such detriments. It is still unclear whether non-invasive brain stimulation may be a solution, but it is worth exploring the potential benefits.

Memory: A review

The Atkinson-Shiffrin (1968) model of memory, also known as the multi-store model or modal model, asserts that there are three separate components of the memory process: sensory memory, short-term memory, and long-term memory (see Figure 1). Sensory information enters the sensory register, an ultra-short memory store for information gathered by the senses (touch, taste, smell, auditory, and visual). Short-term memory, also known as working memory, receives input from both the sensory register or long-term store to be manipulated or quickly recalled. Finally, the long-term store is where rehearsed information from the short-term store is held indefinitely.

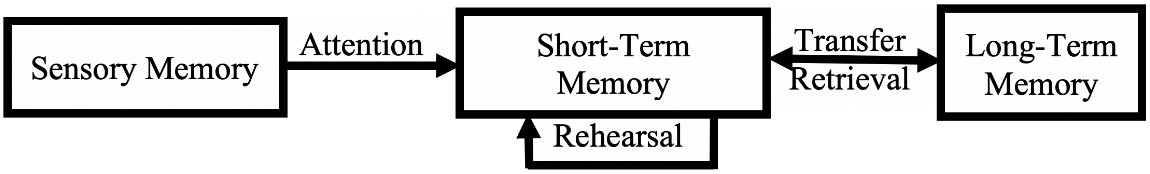

Figure 1. Modal Model of Memory proposed by Atkinson-Shiffrin (1968)

As sensory information is attended to, it is moved to short-term memory where it is retained for a few seconds unless rehearsed by the individual. With additional effort, the information is then transferred to long-term memory for later retrieval or recall. When an individual would like to recall a memory, it is retrieved and brought back to short-term memory for further manipulation. The present study is primarily concerned with working memory and long-term memory and those systems will be further discussed.

Types of memory. The terms short-term memory and working memory are used interchangeably, but working memory is currently the preferred term in the literature. In foundational research conducted by Baddeley and Hitch (1974), the researchers proposed a three-part model of working memory: the central executive, the phonological loop, and the visuospatial sketchpad, that was further expanded to include the episodic buffer (Baddeley, 2000). These systems work together to process and manipulate information based on whether the information is visual or verbal (see Figure 2).

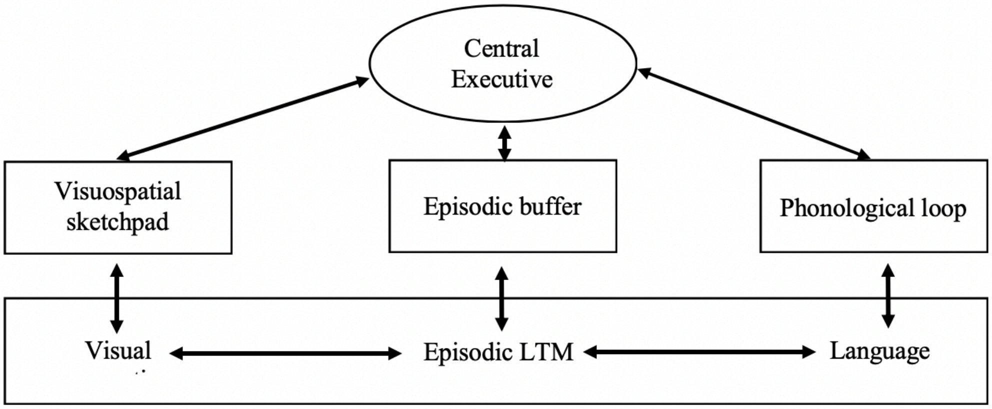

Figure 2. Baddeley and Hitch's (1974) model of working memory with addition of the episodic buffer (Baddeley, 2000).

The central executive is the system that is responsible for the control and regulation of processes within the working memory model and includes functions such as updating information within the system, binding information from multiple sources, coordination of the visuospatial sketchpad and phonological loop, shifting between tasks, inhibition, and selective attention. The phonological loop, or the articulatory loop, works with auditory phonological information. It is considered the mind's "inner voice" and "inner ear." The visuospatial sketchpad works with visual and spatial information that is presented through the eyes. The fourth component of the system, that was added later after the proposal of the original model, is the episodic buffer. This system is the linking component of the central executive, phonological loop, and visuospatial by adding an intermediary buffer for information from the phonological loop and visuospatial sketchpad to be integrated or "chunked" together to be sent to LTM.

This study is primarily interested with working memory but does explore additional questions related to long-term memory (LTM; Tulving, 1989, Squire, 1987). LTM is commonly divided into two primary types of memory, declarative memory and nondeclarative memory. Declarative memory refers to knowledge that we have conscious access to and is further divided into episodic memory, or memory for events, and semantic memory, or memory for facts. Nondeclarative memory refers to knowledge we do not have conscious access to such as procedural memory, or memory for motor and cognitive skills. The present study is primarily concerned with the episodic long-term memory of verbal and musical items.

Musical Working Memory. Working memory may be more complex than the model proposed above. There may be additional components that are not included in the theoretical model but are at play in memory. Berz (1995) asserted that there may be a distinct musical working memory system alongside verbal working memory and the visuospatial sketchpad (see Figure 3). This model was proposed prior to Baddeley's addition of the episodic buffer and thus does not encapsulate all working memory.

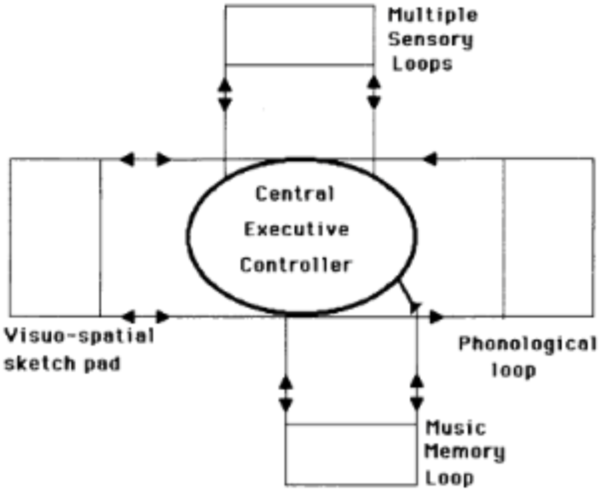

Figure 3. Benz's (1995) Theoretical Model Including Musical Working Memory.

Research has shown that there are some differences in processes of music perception compared to verbal perception. Schulze and Tillmann (2013) found that there were separate working memory processes for timbres compared to words and tones. When participants were presented with sounds that varied in different timbres, outside verbal information did not affect the processing of these timbres during a forward or backward recognition task. This indicates that the two systems may coexist since information from one does not appear to decrease the performance of the other. The findings of this study suggest that verbal working memory may not be a unitary system and may contain several different processes. However, other research has found evidence that musical working memory and verbal working memory may compete for the same processing resources. Williamson, Baddeley, and Hitch (2010) found that there were similar limitations to the short-term memory of tones as compared to verbal working memory, particularly in the number of items that could be held. However, there seemed to be a difference between musicians and non-musicians during performance on the music task, suggesting that musicians may have different strategies for the processing of musical information in working memory. This may be a fruitful area of research.

Non-Invasive Brain Stimulation

Non-invasive brain stimulation refers to a technique of stimulating an area of the brain by external means by modulating the neuronal activity. There are several possible reasons why this technique may be used. The method utilizes a technique that does not require direct access to the brain and thus is generally regarded as a safer technique (Matsumoto & Ugawa, 2017). More specifically, it can be used to enhance some type of processes (e.g. motor or cognitive). There are two primary techniques of non-invasive brain stimulation: transcranial magnetic stimulation, affecting neuronal activity by producing a powerful magnetic field around a specific area of the brain whereas and transcranial electric stimulation, affecting neuronal activity by applying an external current to the brain. There are several variations of transcranial electric stimulation that can be used during non-invasive brain stimulation including Transcranial Direct Current Stimulation (tDCS), Transcranial Alternating Current Stimulation (tACS), Transcranial Pulsed Current Stimulation (tPCS), and Transcranial Random Noise Stimulation (tRNS) (Moreno-Durante et al., 2014). tDCS uses a constant current that is of low intensity, applied directly to the head, and partially penetrates the skull. tACS is like that of tDCS, but the current alternates direction with a sinusoidal motion. tPCS use rectangular waves (applying a constant current, briefly removing the current, switching the polarity of the current, and repeating that process) for stimulation. Lastly, tRNS alternates the current with random amplitude and frequency and intensity. While all of the methods do in general apply a current to the skull, the way it is applied is what differs. Majority of research at the time of this writing has focused on tDCS and tACS, though research has shown tRNS has been more effective than the aforementioned techniques in motor evoked potentials (Inukai et al., 2016). However, there have been few studies comparing these different techniques on cognition. tDCS has been implemented more often than other techniques as it was the first developed. This review will be focusing on tDCS as it was used in the present study.

Transcranial Direct Current Stimulation (tDCS). As mentioned, the tDCS technique includes constant current stimulation to the forehead. However, there are several parameters to consider when planning a tDCS study, which include: size and placement of electrodes, type of stimulation (anodal vs cathodal), and intensity of current (0.5-2mA). The placement of the electrodes corresponds with the International EEG 10-20 system and at least one of the electrodes must be placed on the scalp, while the other can be placed on another cephalic location (on the head) or extracephalic location (away from the head).

The direction of stimulation can be applied either via the cathode (the negatively charged electrode) or the anode (the positively charged electrode). Generally, anodal stimulation increases excitability of neurons, making them more likely to fire action potentials (Boros, Poreisz, Munchau, Paulus, & Nitsche, 2008; Nitsche et al., 2003) and cathodal stimulation decreases excitability (Ardolino, Bossi, Barbieri, & Priori et al., 2005). Thus, the use of anodal stimulation is primarily used to enhance a behavior, whereas cathodal stimulation is used to inhibit a certain behavior. The direction of stimulation polarity changes how the current flows through tissue (Merrill, Bikson, &

Jefferys, 2005). During cathodal stimulation, anions (negatively charged ions) flow through the cathode, through the tissue, and back to the anode. During anodal stimulation, cations (positively charged ions) flow through the anode, through the tissue, and back to the anode. Vogel (2017) offers a good explanation of the exact mechanism of how stimulation affects the potentials of neurons. However, there is plenty of skepticism surrounding the mechanisms of transcranial electric stimulation. For example, Vöröslakos and colleagues (2018) used rodent and cadaver brains to measure how much externally applied current penetrates through the skull. They found that roughly 75% of the current is reduced due to the skull and soft tissue surrounding the area. Furthermore, they found that at least 1 mV/mm voltage gradient is needed for neuronal modulation.

Studies that utilize transcranial electric stimulation generally have three primary between-subject conditions: no device usage, stimulation, and a “sham” stimulation condition. When the sham mode is used on a device, the device begins stimulation for only a couple of seconds and then shuts off. This leads participants to believe that they are receiving stimulation when there is no stimulation occurring. Another consideration of design is whether the task should be completed “online,” where the task is completed during stimulation, or “offline,” where the task is completed after stimulation has occurred. These two approaches have their benefits and downfalls. For example, while online stimulation minimizes the potential for after-stimulation interference, participants may receive different durations of stimulation depending on how long it takes for them to complete a task (e.g. during a recall task, if it takes longer for one participant to recall an item compared to another participant, the participant with the longer recall time would have experienced a longer duration of stimulation). For offline stimulation, all participants receive the same exposure to tDCS, but the temporal gap between stimulation and the task may cause unwanted effects such as a potential decrease in the effect of the stimulation over time. For example, there could be interference from what the participant is doing or thinking during the stimulation period, thus leading to unwanted confounds. This is a concern of tDCS methodology and should be carefully considered when designing a tDCS study.

Studies of tDCS look at both the effects of usage on cognitive performance tasks and in clinical settings to treat mood disorders or other psychiatric issues. Due to the customizable ability of tDCS devices, there is a wide range of study designs. Hill, Fitzgerald, and Hoy (2016) offer a meta-analysis of several tDCS studies. In the meta-analysis, studies were broken down by protocol (e.g. blind, double-blind, counterbalanced, etc.), participant demographics, electrode details (e.g., size and current density), electrode location, timing of cognitive test and stimulation, results, and which cognitive tests were used. The cognitive tasks used by many studies in this meta-analysis include the N-back task (working memory capacity), Sternberg task (item-recognition working memory), backwards and forwards digit span tests (working memory capacity), cognitive batteries that include one or more working memory tests, and a paced auditory serial addition task (auditory information processing speed, flexibility, and calculation). Studies were divided on whether healthy adults or adults with working memory deficits were used as participants.

Though many studies in the Hill, Fitzgerald, and Hoy (2016) meta-analysis reported significant findings on cognition and working memory with tDCS, there has been skepticism of these outcomes. Medina and Cason (2017) suggest that previous meta-analyses have looked specifically at only the outcomes in previous studies and did not consider whether there was adequate statistical power within each study. Their analysis considered a random selection of studies that used tDCS to alter cognitive performance. Using a p-curve analysis, they found that the majority of studies lacked adequate statistical power of 33% or greater. Thus, a major consideration when designing tDCS is the statistical power needed to accurately make a decision on the effects.

There has been an extensive search into how tDCS can modulate and enhance both verbal and visuospatial working memory. Boehringer, Macher, Dukart, Villringer, and Pledge (2013) investigated cathodal tDCS stimulation over the cerebellum and the effect on verbal working memory as those with cerebellar lesions display cognitive deficits. Since cathodal stimulation reduces neuronal excitability, it was expected that the stimulation would mimic similar effects of lesions in the cerebellar area. tDCS stimulation to the cerebellum showed similar effects to those with cerebellar lesions on forward digit span tasks. This similarity suggests that tDCS affects higher cognitive abilities by the induction of “virtual” lesions that cause similar effects as real ones.

While tDCS research is more extensive with verbal working memory, several studies have studied its effects on visuospatial working memory as well. Kyongje and Barry (2018) showed that anodal stimulation improved response times during visual search tasks but did not increase accuracy on these tasks. After slight manipulations of stimulus brightness and electrode placement, visual search task accuracy was still not increased. The researchers propose that tDCS may have a diffuse effect rather than a direct one since there was a change in information processing by increased speed, but not necessarily the actual processing of task information.

The goal of many tDCS studies is to enhance or inhibit a cognitive ability and patient populations are often used to determine whether their cognition can benefit from non-invasive brain stimulation. For example, Monai and Hirase (2018) found evidence of tDCS effectively treating biological processes associated with depression via astrocytic Ca^{2+} modulation. Similarly, the use of tDCS appears to be beneficial in patients with schizophrenia. For example, patients stimulated with 2 mA anodal tDCS perform better on cognitive tasks, especially patients with lower levels of neurocognitive functioning and when those tasks are highly challenging (Schwippel et al., 2018). While there is still much to be discovered about tDCS and its effects on cognitive functioning, it appears to be a topic with much to be explored, especially in those with cognitive impairments.

Horvath, Carter, and Forte (2014) also offer several suggestions and considerations for tDCS study designs. Inter-subject variability and the extensive between- and within-group variation is a concern of tDCS studies. One possible explanation for this is inconsistent placement of electrodes. Since many studies do not use an MRI guided system, slightly offset placement of electrodes may cause an unwanted effect to occur. An alternative explanation may be that the difference of individual anatomy may cause a different effect even when all other conditions are controlled for. Intra-subject reliability is another concern of studies. There is insufficient research looking at the reliability of an individual’s answers on a cognitive task during a study. A low intra-subject reliability may inconsistently lead to either Type I or Type II errors. During tDCS sessions, there needs to be focused consideration of sham stimulation and blinding in studies. When considering the effects of tDCS, they should be compared to proper control conditions, such as sham conditions and baseline performance. In addition, blinding of researchers and participants is also a concern. Simple motor and cognitive interference after stimulation may eradicate any effects of tDCS. Thus, upon completion of a tDCS session and before the end of a study, any motor and cognitive activity should be minimized. Furthermore, there are several factors that may influence the electric current, such as hair thickness. While study procedures use a large amount of saline spread to combat this, the saline may travel to undesirable areas of the scalp and cause stimulation in incorrect places. Sweat can also cause an unwanted effect by increasing the area of conductive ability. While it may not be possible to completely control for these issues in all participants, every effort should be made to minimize them.

The utmost concern when designing a study using non-invasive brain stimulation is the safety of participants. At the time of publication, Matsumoto and Ugawa (2017) reported that there have been no serious adverse effects from experiments using tDCS or tACS. The analysis of experiments showed that the primary complaints of side effects with using tDCS, but not tACS, were itching, tingling, redness, and burning, though only mild. The higher the current, the more care should be used. Aside from cognitive impairments and improvements, which is to be expected from the nature of the stimulation, a small number of participants experienced treatment-emergent mania and hypomania when being treated for major depressive disorder by means of tDCS. According to the authors, no adverse psychological effects such as treatment-emergent mania and hypomania have been reported for healthy participants. Though the adverse effects of tDCS appear to be relatively mild in healthy participants, cautious action and planning should always be the priority.

Purpose of Research

As previously mentioned, Schulze and Tillmann (2013) found there are similarities between tonal and verbal working memory. For example, the word length effect refers to the ability to remember a larger number of shorter words compared to longer words (Baddeley, Lewis, and Vallar, 1984). While verbal and tonal information are susceptible to a length effect in both forward and backwards recognition tasks, other literature has not found a length effect for backward recall with verbal material (Bireta et al., 2010; Suprenant et al., 2011). Schulze and Tillmann (2013) also investigated whether verbal and tonal information were susceptible to articulatory suppression. During articulatory suppression, two simultaneous tasks compete for the same verbal working memory resources (e.g. saying an irrelevant word such as “the” while trying to encode a list of words). They found verbal information was susceptible to articulatory suppression, whereas tonal information was not. Thus, the mechanism for internal/sub-vocal rehearsal for verbal and tonal information may be fundamentally different.

Furthermore, Albouy, Peretz, Bermudez, Zatorre, Tillmann, and Caclin (2018) studied patients with congenital amusia, the inability to perceive pitches (also known as tone deafness), via fMRI and revealed that cortical systems for tonal and verbal-short term information are coexistent. During tonal maintenance, compared to matched control participants, amusics showed decreased activity in the right auditory cortex, inferior frontal gyrus (IFG), and the dorso-lateral-prefrontal cortex (DLPFC). During tonal encoding, amusics exhibited reduced right-lateralized functional connectivity between the auditory cortex and the IFG. In addition, they also exhibited less connectivity between the IFG and DLPFC during tonal maintenance. There were no differences between amusics and control participants during verbal working memory tasks; both exhibited activation in the left IFG and left fronto-temporal connectivity. Amusics did not recruit the right fronto-temporal regions as much during tonal memory compared to verbal memory, while the opposite pattern was found for control participants. This research illustrates the limitations of the current Working Memory model, specifically regarding the handling of phonological information and the distinction between verbal and musical working memory.

The brain regions recruited in certain verbal working memory tasks may be task dependent. While using voxel-based lesion symptom mapping, a neuroimaging technique which allows researchers to investigation the relationship between tissue damage and behavior on a voxel-by-voxel basis, Ivanova and colleagues (2018) investigated the brain regions recruited during a complex listening span task and a word 2-back task. These two tasks are commonly used interchangeably in verbal working memory research, however the brain regions recruited during each task are different. Lesions to the inferior frontal gyrus seem to inhibit performance on the complex span task whereas lesions to the superior and middle temporal gyri are associated with inhibited performance to the 2-back task. The brain regions recruited during a 2-back task are important to note for the present study as this task will be used as the verbal task for the present study.

The left supramarginal gyrus (SMG) has been shown to be associated with pitch memory, especially in non-musicians (Schaal, Krause, Lange, Banissy, Williamson, & Pollok, 2015). Both musicians and non-musicians received cathodal tDCS over the left SMG, right SMG, or sham stimulation while completing various musical tasks. Cathodal stimulation over the left SMG lead to a decrease performance to pitch recognition and pitch recall tasks in non-musicians, but not musicians. Stimulation over the right SMG caused a decrease on the pitch recognition task in musicians only. Thus, the SMG appears to be a key component in musical working memory tasks.

Regarding tDCS and cognition, Talsma, Korese, and Slagter (2017) found that multiple sessions of anodal stimulation on the left dorsolateral prefrontal cortex had mixed effects on verbal n-back task accuracy. A n-back task assesses working memory capacity. Participants are presented with a series of numbers or letters and are required to make a judgement on whether or not the presently shown number/letter is the same as n times before it (i.e. in a 2-back task, participants would judge whether or not the currently shown number/letter is the same as two stimuli previous). While there was a positive effect for some participants, where accuracy was improved, some participants experienced a negative effect where accuracy was decreased, though this only occurred in a few participants. Thus, there may be specific individual differences that may be present that alters the effect of tDCS. This example illustrates the inconsistent and complex nature of tDCS and cognitive enhancement and the need for further explanation.

The purpose of the present study was to investigate whether there are independent systems in working memory for auditory verbal information and musical information via the usage of tDCS. Hypothesis 1 predicted when anodal tDCS is applied over the left SMG, there would be an increase in musical working memory ability, but not necessarily auditory verbal working memory ability. In addition, Hypothesis 2 predicted there should be a difference between performance on the musical working memory task between the active stimulation condition, sham condition, and the behavioral only condition, such that there should be an increase in task accuracy from behavioral only to sham, and a large increase when full stimulation is used. Hypothesis 3 predicted that there would also be a difference between the active stimulation condition in a long-term memory task compared to the sham and behavioral conditions, such that there would be greater accuracy in musical LTM accuracy scores. While Schaal and colleagues (2015) found that tDCS affected musical WM, it may be possible that LTM might be affected as well, though previous literature has not yet addressed this question. Finally, Hypothesis 4 predicted that there would be greater confidence in musical LTM judgements compared to verbal judgements and that these judgements would be associated with actual performance. Though previous research has shown that confidence is unaffected by tDCS stimulation in a verbal task (Javadi & Cheng, 2013), confidence during an LTM musical task with tDCS has not been assessed. In addition, previous research has shown that participants judge their confidence higher in LTM judgements when the items are musical compared to purely verbal (Finch, Stern, & Deason, 2019).

II. METHOD

Participants

Seventy-four young adults (M_{age} = 18.76, SD_{age} = 1.04, 81.9% female) participated in this study, however two participant's data were excluded due to data recording errors (see Table 1 for specific demographics for each tDCS group). Inclusion criteria for this study included a requirement to be right-handed, normal or corrected-to-normal vision and hearing, and no prior or current neurological problems or complaints. The participants were recruited through the Texas State University SONA participant recruitment pool and through posted advertisements. Participants received either course credit through the SONA system or cash compensation at $10 per hour. This study was funded by the Texas State University Graduate college through the Thesis Research Support Fellowship and was approved by the Texas State University Institutional Review Board.

Table 1

Demographics for Between Subjects Conditions (tDCS)

tDCS Condition	Age	% Male	% Female
Behavioral	18.88 (1.15)	79.2	20.8
Full	18.75 (1.13)	79.2	20.8
Sham	18.67 (0.87)	87.5	12.5

Materials and Design

The design of this study was a mixed-factorial design where the between-participants factor was the tDCS stimulation condition (no-stimulation/behavioral, sham, and full stimulation) and the within-subjects factor was working memory task type (musical working memory and verbal working memory). Accuracy and reaction time were recorded for each trial. This design was selected over a within-participants design where all participants receive each condition at different times for several reasons. First, as participants experience a task several times, their performance may increase from constant exposure thus leading to a need for adaptive task difficulty (Flegal, Ragland, & Ranganath, 2019). Second, there was a concern of the attrition of participant attendance; it is possible that many participants may not come back for multiple sessions. Third, there is no research at this time that has investigated how long tDCS may affect the SMG. Fourth, there is an issue of idiosyncratic neuroanatomical factors across comparison groups. The concern is that skull and skin thickness as well neuroanatomic geometry can cause confounds across comparison groups. Between-group differences in such factors might cause different levels of tDCS signal intensity to reach the cortex for each group on average, which in turn might produce differential behavioral outcomes between groups. However, applying a difference score for the outcome measures can correct for this issue because such between-group confounds are removed when computing the difference via the mathematical operation of subtraction. This is discussed further in the results section.

tDCS Device. The materials used for tDCS stimulation are generally two saline-soaked sponges, electrodes, non-conductive straps, cables, and the tDCS stimulator device (DaSliva, Voltz, Bikson, & Fregni, 2011). The sponges must be the same shape and size to ensure proper uniform distribution of the current and the size of each sponge is generally 20-35 cm^2. A Foc.us v2 (London, England) transcranial stimulation device was used as the tDCS device. This device's capabilities included: tDCS or tACS, a maximum of 2.0mA at 29K Ohms, supports 1 anode and 1 cathode, and maximum DC output of 58V. The electrodes used were two 2 x 2 inch Amrex electrodes comprised of a conductive metal mesh backing encased by a rubber shell supplied by Caputron (New

York, NY). The sponges attached to the electrodes were soaked in a 0.9% sterile saline solution supplied by Covidien (Mansfield, MA). This device was not designed for research purposes, but rather for commercial use. Commercial devices like the Foc.us v2 are used casually (as marketed) for improvement on various tasks such as musical training, sports, or video game playing.

Figure 4. Foc.us v2 Stimulation Device

Questionnaires. Two questionnaires were used in this study: the Goldsmiths Musical Sophistication Index (Gold-MSI; Müllensiefen, Gingras, Musil, & Stewart, 2014) and a post-experiment survey. The Gold-MSI was created to measure a participant's musical sophistication. The index assesses seven independent dimensions: importance of music in everyday life, perception and production abilities of music, musical training, emotion, bodily movement associated with music, musical creativity, and openness to attend cultural music events or new music. The purpose of the Gold-MSI in the present study was to assess the overall musical ability of the participants and investigate any pattern of musical sophistication across the different between-participant conditions.

The post-experiment survey was used to assess any issues that the participants had with the study, asked about any strategies they may have used during the working memory tasks, and their overall experience with the study. While no formal statistical tests were conducted on these responses, the responses were used to evaluate the overall design and effectiveness of the study.

Memory Tasks. Each participant completed two working memory tasks: one to assess verbal working memory and one to assess musical working memory. Both tasks were variations on an identical task, a n-back task, so that there may be a clear comparison between verbal and musical performance. In addition to identical type of task, the presentation of the stimuli was also similar. In the verbal WM task, participants heard four letters spoken at a rate of one letter a second and were asked to judge whether each trial was the same as the one that had preceded it two previous. There was a total of 100 trials each lasting 4000ms each. In the musical working memory task, each trial consisted of a short four note melody played at 60 bpm (total length of 4000 ms). There were 100 trials of the musical WM task as well. Each set of four note melodies were diatonic in nature (i.e., no notes outside the key signature) and were played in the key of C major. The stimuli were presented via special headphones designed to be compatible with EEG recording.

Upon completion of the two working memory tasks, the participants completed a long-term memory task. The purpose of this task was to assess if tDCS effects are specific to working memory, or if the effects might extend to other areas of memory such as long-term memory. Fifty musical stimuli and fifty verbal stimuli were presented to the participant. Of the 100 total stimuli, the participant heard fifty of them during the first two tasks (25 verbal, 25 musical), and the remaining fifty were novel (25 verbal, 25 musical). The participants made a judgement of whether they heard the stimuli previously during the WM task. After each judgement, participants were presented with a 5-point Likert scale asking them to judge how confident they were in their answer. Each point was labeled with a number 1-5 as well as a percentage (1 was 0% confident, 2 was 25% confident, 3 was 50% confident, 4 was 75% confident, and 5 was 100% confident).

Procedure

Upon arrival to the lab, participants read and signed the consent form. The procedure of the study varied based on the experimental condition the participant was randomly assigned to complete. In the behavioral condition, participants first completed the Gold-MSI questionnaire and then completed the two working memory tasks. The order of the tasks (i.e. musical then verbal or verbal then musical) was counterbalanced across participants. In the sham and the stimulation conditions, participants were first setup with the Foc.us 2 device with the electrodes placed over the left supramarginal gyrus (SMG) in correspondence with the international 10/20 system. The closest scalp location to the SMG, or Brodmann area 40, is CP3. The anode was placed over CP3 with the cathode placed over an adjacent electrode site, CP5 (see Figure 4). Participants who were in the sham and full stimulation category were fitted with a 64 channel EEG cap and measurements were taken to ensure point CZ was centered. The electrodes were then placed underneath their respective locations while the EEG cap held them in place. These sites were chosen based on previous studies attempting to stimulate the SMG (Antal, Nitsche, Kruse, Kincses, Hoffmann, & Paulus, 2004; Rogalewski, Breitenstein, Nitsche, Paulus, & Knecht, 2004; Vines, Schnider, & Schlaug, 2006). Schaal, Karuse, Lange, Banissy, Williamson, and Pollok (2015) found that cathodal stimulation over the left SMG decreased performance on pitch memory tasks for non-musicians whereas there was no difference on the same task for musicians compared to no stimulation. Since the anticipated sample for this study was non-musicians, the same type of setup was implemented.

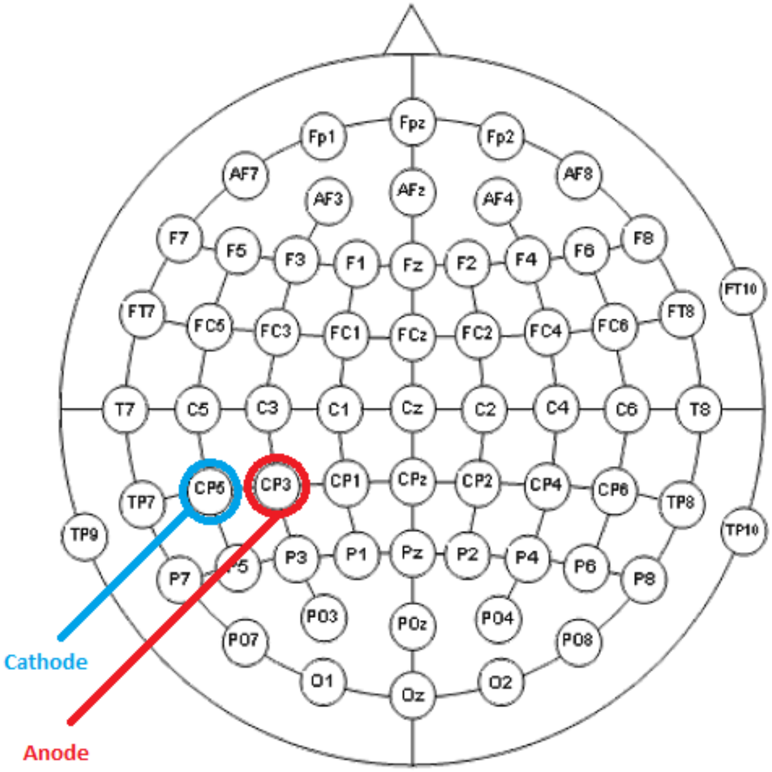

Figure 5. Placement of tDCS electrodes.

The device parameters were set to 1.0 mA current intensity and anodal stimulation. During the initiation of the stimulation period, the Foc.us 2 device began ramping up the voltage by increasing it slowly from 0 mA to 1mA over the course of about 30 seconds. This was to minimize any adverse effects of applying an electrical current to skin. In the sham condition no electrical current was applied, but the device showed signs of current being applied on the device readout. During the 20-minute stimulation period, the participant completed the Gold-MSI. The researcher occasionally checked the tDCS device to ensure the readout continued to show 1.0 mA stimulation and adjusted electrodes if needed. Though the sham condition did not actually provide any stimulation, the researcher still ensured the readout showed 1.0 mA and made adjustments if the device was not reaching full current potential. After the completion of the stimulation period, the participant completed both the musical working memory task and the verbal working memory task, which was counterbalanced across participants. Participants then completed the long-term memory task and the post-experimental questionnaire.

III. RESULTS

Demographic Comparisons

To determine whether demographics differed significantly between stimulation groups, an ANOVA of age across stimulation conditions and a Chi-Square Test of Independence between gender and stimulation condition was conducted. There was no significant difference in age across the different stimulation conditions, $F(2, 69) = 0.238$, $p = .789$, $\eta^2 = .007$. Furthermore, there were no significant differences in frequency of gender across stimulation conditions, $\chi^2(2) = 0.751$, $p = .687$.

Gold-MSI Analysis

To assess the sample's overall musical sophistication, Gold-MSI subscales (active engagement, perceptual ability, musical training, singing ability, emotions, and general sophistication) were compared to the normative population.

Table 2

Study sample vs. Gold-MSI population

	Population		Participants				
	M	*SD*	*M*	*SD*	*p*	*d*	*α*
Active Engagement	41.52	10.36	38.39	6.26	< **.001**	0.37	.651
Perceptual Ability	50.20	7.86	44.34	6.54	< **.001**	0.81	.727
Musical Training	26.52	11.44	19.96	8.85	< **.001**	3.57	.836
Singing Ability	31.67	8.72	29.69	7.47	**.034**	0.24	.658
Emotions	34.66	5.04	31.79	4.73	< **.001**	0.59	.787
General Sophistication	81.58	20.62	70.43	14.40	< **.001**	0.63	.891

To determine if participant's musical sophistication might serve as a confound between the between-participations stimulation conditions, a series of one-way ANOVAs were conducted where the dependent measures were the Gold-MSI subscales and the independent variable was the stimulation condition (behavioral, sham, or full stimulation). There was a significant difference in active engagement scores across tDCS conditions, $F(2, 62) = 3.616, p = .033, \eta^2 = .099$. According to Tukey's HSD post-hoc test, those in the sham condition ($M = 41.04, SD = 6.29$) had significantly higher active engagement scores than those in the behavioral condition ($M = 36.38, SD = 5.76$). There was a significant difference in perceptual ability scores across stimulation conditions, $F(2, 64) = 3.371, p = .041, \eta^2 = .095$. According to Tukey's HSD post-hoc test, those in the sham condition ($M = 46.96, SD = 5.25$) had significantly higher perceptual ability scores than those in the behavioral condition ($M = 42.33, SD = 8.33$). There was not a significant difference in musical training scores across stimulation conditions, $F(2, 64) = 0.284, p = .284, \eta^2 = .011$. There was not a significant difference in emotion scores across tDCS stimulation conditions, $F(2, 64) = 2.091, p = .132, \eta^2 = .049$. There was not a significant difference in singing ability scores across tDCS stimulation conditions, $F(2, 64) = 1.816, p = .171, \eta^2 = .058$. There was not a significant difference in general sophistication scores across tDCS stimulation conditions, $F(2, 64) = 0.613, p = .613, \eta^2 = .019$. Since the effect sizes of significant Gold-MSI comparisons across stimulation conditions were not large, these were not controlled in subsequent analyses.

WM Accuracy Analysis

To assess the effect of tDCS on verbal vs. musical WM accuracy, a three-way ANOVA was conducted where the between-subject variables were the stimulation condition (behavioral, sham, or full stimulation) and the WM task order (musical first or verbal first) and the within-subject variable was WM task (musical or verbal), and the dependent measure was the accuracy on these tasks. There was a significant main effect of task type in verbal WM scores (*M* = .659, *SD* = .088) and musical WM scores (*M* = .625, *SD* = .084), such that participants performed better on the verbal task, when collapsing across stimulation conditions, $F(1, 66) = 11.618$, $p = .001$, $\eta^2 = .150$, 1-β = .919. However, there was not a significant tDCS stimulation condition main effect, $F(2, 66) = 1.517$, $p = .227$, $\eta^2 = .044$, 1-β = .312. There was no main effect of task order, $F(1, 66) = 0.015$, $p = .904$, $\eta^2 = .000$, 1-β = .052. As for interactions, there was not a WM task by stimulation condition interaction, $F(2, 66) = 1.014$, $p = .368$, $\eta^2 = .030$, 1-β = .220, no WM task by task order interaction, $F(1, 66) = 0.033$, $p = .857$, $\eta^2 = .000$, 1-β = .054, and no stimulation condition by task order interaction, $F(1, 66) = 1.498$, $p = .231$, $\eta^2 = .043$, 1-β = .308. There was a significant WM task by stimulation condition by task order interaction, $F(2, 66) = 4.247$, $p = 0.018$, $\eta^2 = .114$, 1-β = .724. Due to the complex nature of the three-way interaction, this is further explored in the subsequent analysis.

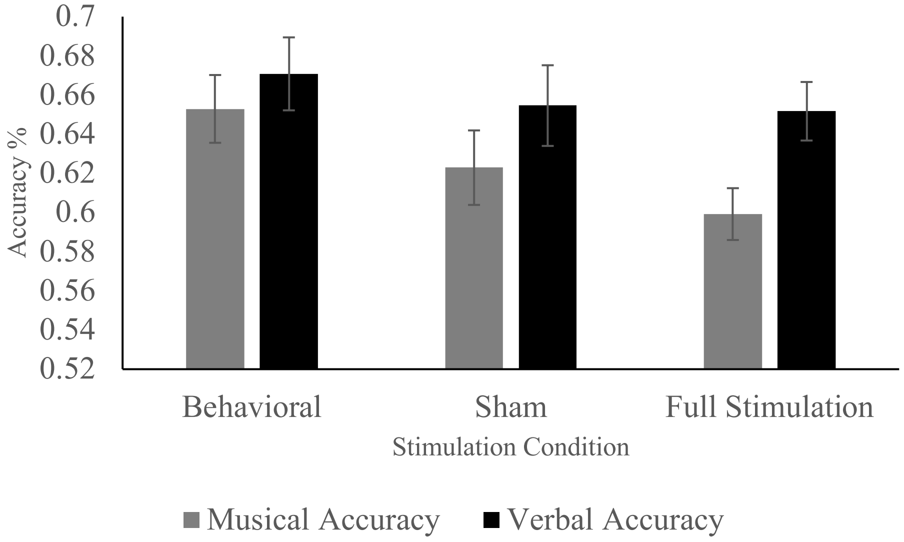

Figure 6. Differences in musical and verbal WM task accuracy across tDCS stimulation conditions.

In order to address the issue of idiosyncratic neuroanatomical factors across stimulation groups, a difference in musical WM scores and verbal WM scores was calculated by subtracting verbal WM scores from musical WM scores. A score of 0 would indicate no difference between tasks. A two-way ANOVA was conducted to assess whether there was a significant difference of these scores, the dependent variable, between the between-subjects stimulation group factor and the within-subjects factor of which task was presented first. There was no significant difference in the difference of WM scores between full (M = -0.053, SD = 0.090), sham (M = -.032, SD = 0.074), and behavioral (M = -0.018, SD = 0.099) conditions, $F(2, 66) = 1.014$, $p = .368$, $\eta^2 = .030$, 1-β = .220, nor was there difference in which order the tasks were presented, $F(1, 66) = 0.033$, $p = .857$, $\eta^2 = .000$, 1-β = .054. There was, however, a stimulation condition by order interaction, $F(2, 66) = 4.247$, $p = .018$, $\eta^2 = .114$, 1-β = .724. According to simple main effect pairwise comparisons, when the verbal task was presented first there was a significant difference between the behavioral condition (M = .020, SD = .089) and full stimulation condition (M = -.086, SD = .100), such that those in the behavioral condition had a higher accuracy on the musical task whereas those in the full stimulation condition had a higher accuracy on the verbal task.

WM Reaction Time Analysis

To assess the effect of tDCS on verbal vs. musical WM reaction time, a two-way ANOVA was conducted where the between-subject factor was stimulation condition (behavioral, sham, or full stimulation), the within-subject factor was WM task order (musical first or verbal first), and the dependent measure was reaction time on these tasks. There was a significant difference in verbal WM reaction time compared to musical WM, *F*(1, 66) = 12.584, *p* = .001, η^2 = .160, 1-β = .938. Participants reacted quicker to musical stimuli (*M* = 1218.29 ms, *SD* = 586.22) than verbal (*M* = 1481.68 ms, *SD* = 832.85). There were no significant main effects of stimulation condition, *F*(2, 66) = 1.803, *p* = .173, η^2 = .052, 1-β = .364, nor WM task order, *F*(1, 66) = 0.540, *p* = .465, η^2 = .008, 1-β = .112. There was a WM task type by stimulation condition interaction, *F*(2, 66) = 4.081, *p* = .021, η^2 = .110, 1-β = .706, and a WM task type by task order interaction, *F*(1, 66) = 13.526, *p* < .001 , η^2 = 170, 1-β = .952. There was not a WM task type by stimulation condition by WM task order interaction, *F*(2, 66) = 1.212, *p* = .304, η^2 = .035, 1-β = .256, nor a stimulation condition by task order interaction, *F*(2, 66) = 0.882, *p* = .419, η^2 = .026, 1-β = .196. Due to the complex nature of the interactions, the differences are further explored in the subsequent analysis.

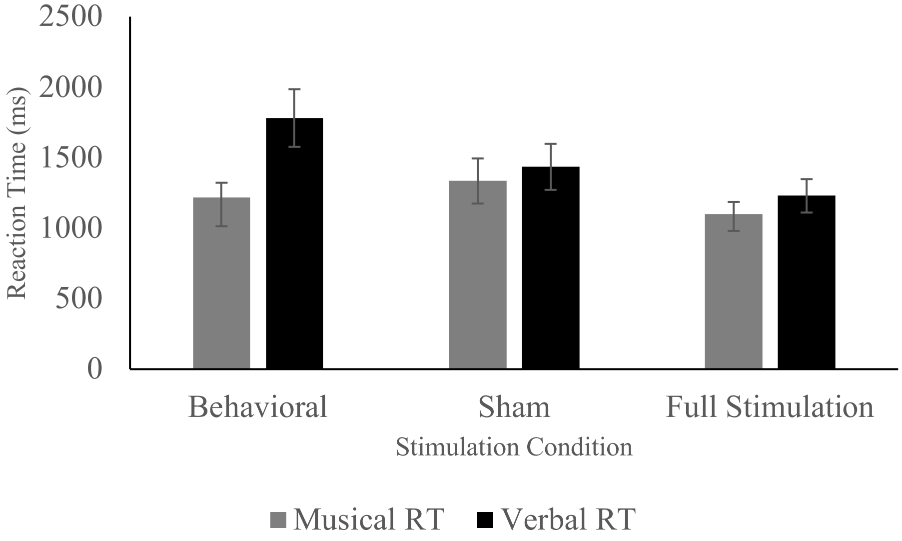

Figure 7. Differences in musical and verbal WM reaction times across tDCS stimulation conditions.

In order to address the issue of idiosyncratic neuroanatomical factors across stimulation groups, a difference in musical WM RTs and verbal WM RTs was calculated by subtracting verbal WM RTs from musical WM RTs. A difference of 0 would indicate no difference in reaction times between tasks. A two-way ANOVA was conducted to assess whether there was a significant difference of these scores, the dependent variable, among the between-subject factor of stimulation groups and the within-subject factor of task order. There was a significant main effect of stimulation condition where there was a bigger RT difference in behavioral (M = -562.771, SD = 914.117) compared to sham (M = -98.033, SD = 518.992), and a trending difference between behavioral and the full stimulation condition (M = -130.363, SD = 556.144), $F(2, 66) = 4.081$, $p = .021$, $\eta^2 = .110$, $1-\beta = .706$. In addition, there was a significant main effect of the task order, such that there was a larger difference for the verbal task first (M = -536.458, SD = 652.246) compared to the musical first (M = 9.679, SD = 652.683), $F(1, 66) = 13.526$, $p < .001$, $\eta^2 = .035$, $1-\beta = .256$.

LTM Accuracy Analysis

To assess the effect of tDCS on verbal vs. musical LTM accuracy, a two-way ANOVA was conducted where the between-subject factor was the stimulation condition (behavioral, sham, or full stimulation) and the within-subject factor was LTM task (musical or verbal), and the dependent measure was accuracy on these tasks . There was a significant difference in verbal LTM task scores (M = .513, SD = .067) vs. musical LTM task scores (M = .537, SD = .068) such that participants performed better on musical items, $F(1, 69) = 5.119$, $p = .027$, $\eta^2 = .069$, $1-\beta = .607$. There was no significant LTM task by tDCS condition interaction, *F*(2, 69) = 1.349, *p* = .266, η^2 = .038, 1-β = .282. Furthermore, there was no significant difference in LTM scores across tDCS stimulation conditions, *F*(2, 69) = 1.818, *p* = .170, η^2 = .050, 1-β = .367.

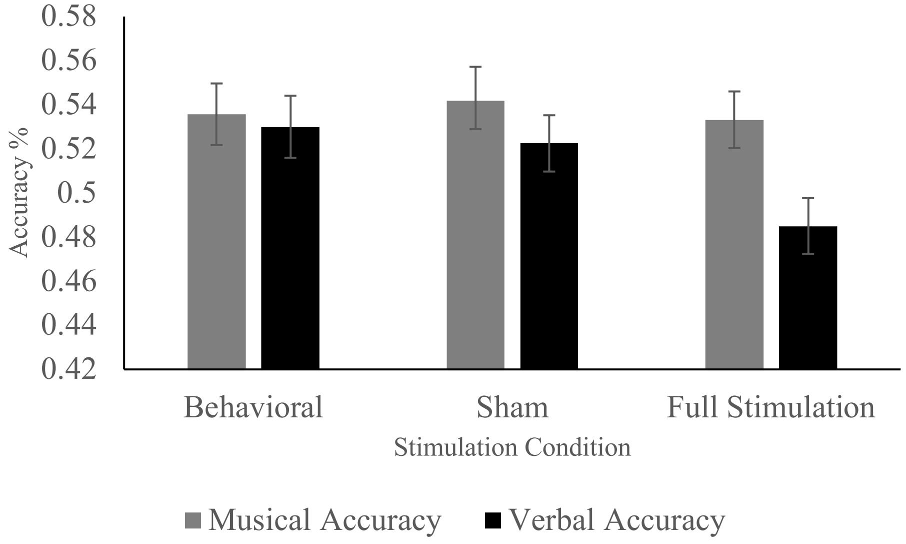

Figure 8. Differences in musical and verbal LTM task accuracy across tDCS stimulation conditions.

In order to address the issue of idiosyncratic neuroanatomical factors across stimulation groups, a difference in musical LTM scores and verbal LTM scores was calculated by subtracting verbal LTM scores from musical LTM scores. A score of 0 would indicate no difference between tasks. A one-way ANOVA was conducted to determine if there was a difference in these scores, the dependent measure, and the between-subjects factor of stimulation condition. There was no difference in the difference of LTM scores between full (*M* = 0.048, *SD* = 0.096), sham (*M* = 0.019, *SD* = 0.098), and behavioral (*M* = 0.006, *SD* = 0.080) conditions, *F*(2, 69) = 1.349, *p* = .266, η^2 = .038, 1-β = .282.

LTM Reaction Time Analysis

A two-way ANOVA was conducted to assess if there was a difference in LTM reaction times, the dependent measure, among the between-subject factor of stimulation condition and the within-subject factor of stimuli type (musical or verbal). There was a significant difference in verbal LTM task reaction times vs. musical LTM task reaction times, $F(1, 69) = 37.020$, $p < .001$, $\eta^2 = .349$, $1\text{-}\beta = 1.000$. Participants reacted quicker to musical stimuli ($M = 1773.851$ ms, $SD = 775.935$) than verbal stimuli ($M = 2436.229$ ms, $SD = 1208.774$). No significant LTM task by tDCS condition interaction was observed, $F(2, 69) = 0.389$, $p = .679$, $\eta^2 = .011$, $1\text{-}\beta = .110$. There was not a significant difference in LTM scores across tDCS stimulation conditions, $F(2, 69) = 2.028$, $p = .139$, $\eta^2 = .056$, $1\text{-}\beta = .405$.

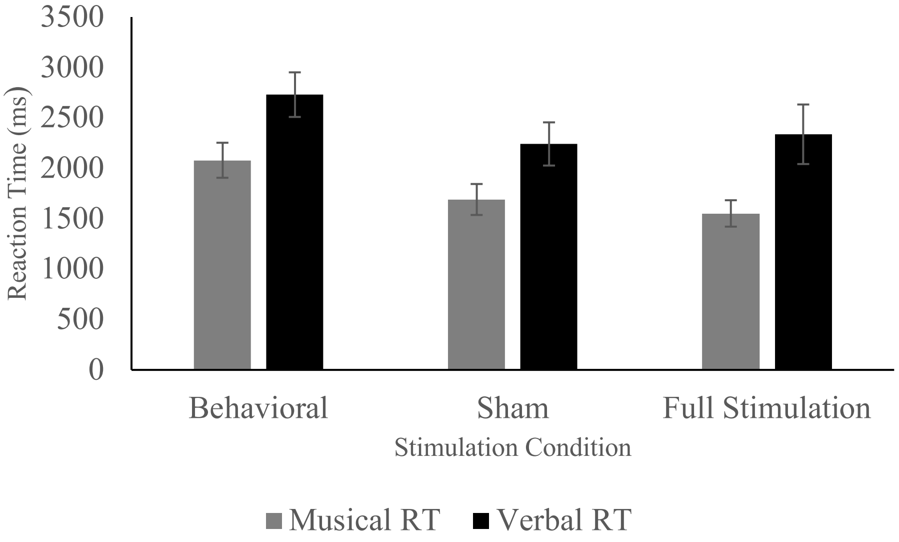

Figure 9. Differences in musical and verbal LTM reaction time across tDCS stimulation conditions.

LTM Confidence Analysis

Participants responded how confident they were on a five-point Likert scale ranging from 0% confident to 100% confident after each trial decision on the LTM memory judgements. A two-way ANOVA was conducted to assess whether there was a difference in confidence, the dependent measure, and the within-subject independent variable of stimuli type (musical or verbal) and between-subject variable of stimulation condition. There was a significant difference in confidence of musical stimuli vs. verbal stimuli, $F(1, 69) = 43.568$, $p < .001$, $\eta^2 = .387$, $1\text{-}\beta = 1.00$, such that participants had higher confidence for musical stimuli ($M = 3.458$, $SD = 0.571$) compared to verbal stimuli ($M = 3.157$, $SD = 0.581$). There was no significant LTM confidence by tDCS stimulation condition interaction, $F(2, 69) = 0.213$, $p = .809$, $\eta^2 = .006$, $1\text{-}\beta = .082$, nor was there a significant difference in confidence ratings between tDCS stimulation conditions, $F(2, 69) = .269$, $p = .765$, $\eta^2 = .008$, $1\text{-}\beta = .091$.

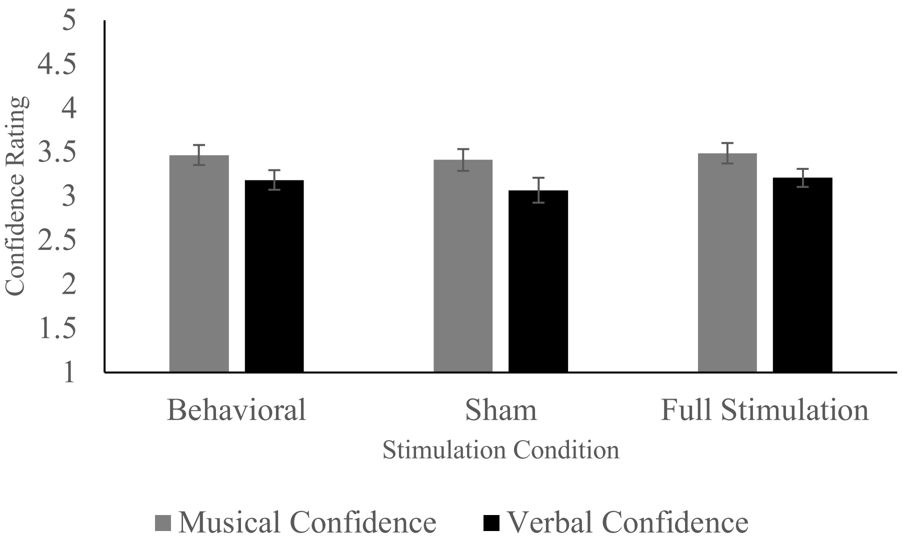

Figure 10. Average confidence ratings in LTM task by tDCS condition.

Goodman-Kruskal Gamma correlations were calculated to assess the relationship between confidence ratings and recognition accuracy for each participant and for each tDCS condition. One sample t-tests between mean gammas for each of the stimulation conditions were conducted to see if scores were significantly different than 0, indicating that accuracy and confidence are associated. Behavioral condition gammas were not significantly different than 0, $t(23) = 0.445$, $p = .661$, $d = 0.091$, sham condition gammas were significantly different than 0, $t(23) = 2.962$, $p = .007$, $d = 0.605$, and full stimulation condition gammas were significantly different than 0, $t(23) = 2.649$, $p = .014$, $d = .541$. However, there were no significant difference in gammas between all stimulation conditions, $F(2, 69) = 1.795$, $p = .174$, $\eta^2 = .049$.

Correlations of Measures

A series of bivariate Pearson correlations, with adjustments for multiple comparisons using Holm's method, were run between the behavioral accuracy, reaction time, and confidence (see Table 3). While there were many significant correlations, only meaningful ones are considered here. There was a significant positive correlation between the verbal and musical WM task accuracies, a positive significant correlation between verbal WM reaction time musical WM reaction time, a positive significant correlation between LTM musical reaction time and both musical and verbal reaction time, a positive significant correlation between verbal LTM reaction time and musical LTM reaction time, and a positive significant correlation between musical item confidence and verbal item confidence.

Table 3

Correlations of Accuracy, Reaction Time, and Confidence

	WM-M-Acc	WM-V-Acc	LTM-M-Acc	LTM-V-Acc	WM-M-RT	WM-V-RT	LTM-M-RT	LTM-V-RT	M-Conf	V-Conf
WM-M-A	-									
WM-V-A	**.478***	-								
LTM-M-A	0.026	-0.037	-							
LTM-V-A	-0.06	0.027	0.073	-						
WM-M-RT	-0.012	0.206	-0.077	0.138	-					
WM-V-RT	0.08	0.127	0.002	0.23	**.546****	-				
LTM-M-RT	0.036	.245	-0.019	.357	**.623****	**.546****	-			
LTM-V-RT	0.055	0.155	0.013	0.191	.351	.394	**.653****	-		
M-Conf	-.298	-0.16	-0.087	0.187	-0.185	-0.176	-0.193	-.167	-	
V-Conf	-.313	-0.224	-.240	0.115	-0.201	-0.183	-0.196	-.255	**.779****	-

Note: * p < .05; ** p < .001; WM-M-Acc = Working Memory Musical Accuracy; WM-V-Acc = Working Memory Verbal Task Accuracy; LTM-M-Acc = Long-Term Musical Memory Accuracy; LTM-V-Acc = Long-Term Verbal Memory Accuracy; WM-M-RT = Working Memory Musical Task Reaction Time; WM-V-RT = Working Memory Verbal Task Reaction Time; LTM-M-RT = Long-Term Musical Memory Reaction Time; LTM-V-RT = Long-Term Verbal Memory Reaction Time; M-Conf = LTM Musical Confidence; V-Conf = LTM Verbal Confidence.

IV. DISCUSSION

The purpose of this study was to investigate whether there are neural dissociations between musical and verbal WM using tDCS. It was hypothesized that there are two distinct working memory subsystems within the phonological loop; one for musical information and one for verbal information. Second, it was hypothesized that tDCS would enhance musical WM when anodal stimulation was applied to the left SMG. Third, it was hypothesized that tDCS would enhance musical LTM. Finally, it was hypothesized that participants would be more confident in their LTM judgements for musical stimuli compared to verbal.

This study sought to investigate these hypotheses by means of a mixed-factorial design where participants were exposed to all memory tasks (within-subjects factor) and to one of three tDCS stimulation conditions (between-subjects factor). Age, gender, and Gold-MSI scores were collected for each participant in anticipation of removing potential confounding effects that could have occurred between tDCS groups. While there were differences in participants' active engagement and perceptual ability subscales, these were not controlled for as their effect sizes were relatively low (Cohen, 1988).

Working Memory Accuracy & Reaction Time

There was a significant difference in WM stimuli condition, such that participants performed better with verbal information compared to musical in terms of accuracy. However, this finding does not necessarily provide information about the processing of information in WM, but rather one stimuli type may have been more difficult than the other. While the tasks were equated as much as possible, the spoken and tonal information might be fundamentally processed differently. A recently published study showed that the neural pathways for verbal and musical information are fundamentally different, such that speech content is processed in the left auditory cortex and melodic content is processed in the right auditory cortex (Albouy, Benjamin, Morillon, & Zatorre, 2020). While the methodology of the present study was based on previous research that found that the left SMG is associated with tonal memory processing in non-musicians (Schaal, Krause, Lange, Banissy, Williamson, & Pollok, 2015), the neural pathways for tonal processing may not be straight forward. Since the left hemisphere is dominant for language processing, left hemisphere stimulation may be more prominent for verbal tasks compared to musical. Future research should continue to investigate areas associated with musical WM and LTM but should also acknowledge that too many brain regions may be involved in processing to be able to stimulate just one. In addition, there is uncertainty of whether only the SMG was being stimulated or if nearby regions may have been affected as well. While this study did not find evidence of separate WM processes, it is possible that these separate processes do exist, but incorporate a more widespread neural network that tDCS might not be able to single handedly enhance.

There were no significant findings when evaluating the use of tDCS on WM accuracy. When evaluating all conditions as together there were no significant differences found between any of the conditions. Since the sham condition was essentially a placebo condition and was very similar to the behavioral condition, a comparison was conducted between the behavioral condition and the full stimulation condition and did not reveal any significant findings. One perplexing discovery was that order of the stimuli seemed to make a difference when considering the accuracy on the WM tasks such that there were significant differences between the stimulation conditions when the verbal task was presented first. However, this finding cannot be explored without further experimental manipulation. Thus, in the context of verbal and musical WM, tDCS did not seem to have an effect when stimulation was applied over the left SMG.

When considering reaction time, the findings are slightly different compared to accuracy, thus there might be a trade-off between speed and accuracy. Participants' reaction time for musical WM stimuli was quicker than verbal WM stimuli. In addition, there was a task by stimulation condition interaction. When considering simple main effects, there was a significant difference in reaction time within the verbal task between the behavioral and full stimulation condition where participants performed quicker during the full stimulation. Based on the positioning of the tDCS device, a difference should have been observed within the musical task. However, this finding does provide some evidence that the tDCS stimulation does have an effect on the speed of verbal information processing but not necessarily how its processed. Since there were additional interactions when considering WM task order, further experimental manipulation is needed to decipher this effect.

Long-Term Memory Accuracy & Reaction Time

When assessing LTM accuracy, there was a significant difference between accuracy of musical stimuli and verbal stimuli with participants performing better on the musical items. This finding alone does not provide much information about LTM as the finding only suggests that correctly identifying one type of stimuli was harder than the other. Similar to the WM task accuracy analysis, the neural pathways for the processing of musical and verbal information may be fundamentally different. However, what remains unclear is why there was an opposite effect for WM and LTM in accuracy, but not in reaction time measures. When considering LTM reaction time, participants reacted quicker to musical items compared to verbal items. There appears to be a disconnect between accuracy and reaction time, but the reason for this is unknown. Future research should investigate this paradoxical finding. When considering all stimulation conditions, there were no significant differences between any of the conditions. While there appears to be no research looking at musical items using a long-term memory recognition task and tDCS stimulation, Jones, Gozenman, and Berryhill (2014) investigated whether tDCS applied unilaterally to the left posterior-parietal cortex could improve verbal LTM. Their findings suggest that the stimulation seems to have an effect while applied during the encoding of verbal items which are later recalled regardless if there is delay or not. While the methodological design of the aforementioned study and the present study are quite different, the investigation of tDCS and LTM using different types of stimuli should be further explored.

Confidence

Confidence was assessed after each trial during the LTM task. Participants reported greater confidence when the information being tested was musical in nature. Despite research being conducted about music’s effect on memory, the investigation of music’s effect on confidence during memory judgements is quite limited. Finch, Stern, and Deason (2019) found that participants report higher confidence in recognition judgements of sung lyrics compared to spoken lyrics and participants were accurate in their decision. In addition, participants exhibited higher confidence in musical stimuli when correctly judging the source (sung vs. spoken) of an item. The present study found a similar finding, though the stimuli that each study used were different. Whereas the present study used small melodies played on a piano and spoken letters, the aforementioned study used spoken and sung lyrics. Considering both studies indicate there may be an association between confidence judgements and music, future research should continue to investigate this potential association.

Goodman-Kruskal Gammas have been used primarily in Judgements of Learning (JOL) to gain insight into memory monitoring and accuracy. This technique was employed to investigate whether a participant's judgement of their decision was related to their actual performance of the LTM task. Kelemen (2000) implemented this technique in a study to investigate whether participant's confidence judgements were related to their accuracy during a test phase. Participants studied items in different categories during a study phase and then recalled these items during a test phase. This study showed that confidence and accuracy are associated, especially when the recall is soon after encoding compared to when there is a delay in recall. The present study used a similar procedure, but participants were not instructed that the stimuli they heard during the WM task would be later tested in an LTM test phase. The results from this study suggest that confidence and accuracy were associated with accuracy only in the sham and full stimulation conditions and there was no significant difference of Gammas between stimulation conditions. It may be that something about the presence of the tDCS device may have impacted this association. Research should consider investigating confidence in tasks in other cognitive areas when using tDCS to determine whether the presence of the tDCS device itself may boost confidence.

Limitations and Future Directions

The demographic characteristics of this sample were a limitation in this study. While participants were all young adults, which prevented any effects of age from interfering with results, the sample was overwhelmingly female. Despite this limitation, previous research has found that gender differences do not seem to influence musical memory when assessing pitch memory in children (Jakubowski, Mullensiefen, & Stewart, 2016) or in young adults when assessing memory for timbre using event-related potentials (Hantz, Marvin, Kredilick, & Chapman, 1996). While gender differences may not affect the outcomes of the present study, a more representative sample may be desired for future research.

The Gold-MSI assesses participant's musical sophistication on several subscales (active engagement, perceptual ability, musical training, singing ability, emotions, and general sophistication). When comparing the present study's sample to the normative values provided by the Gold-MSI (see Müllensiefen, Gingras, Musil, & Stewart, 2014), the present study scored significantly lower indicating less experience in these areas. The Gold-MSI has been shown to be well correlated with other aural tasks such as being able to play a melody by ear (Zhang, Schubert, & McPherson, 2019). Effect sizes ranged from relatively small effects to very large effects (Cohen, 1988). The present sample's musical training was not only significantly lower than the population but showed a very large difference. A significant difference between tDCS stimulation condition regarding musical training would be a greater concern as this could be an alternative explanation for findings, but this was not observed. Future research may attempt to match the sample to the population on this aspect of musical experience but may not be a crucial unless a between-subjects effect is observed. Despite these concerns, a primarily non-musician sample was anticipated when designing this study and thus certain aspects of this study (e.g. brain region of interest for tDCS stimulation) were chosen to anticipate this limitation.

One potential methodological limitation of this study is the stimulation current that was chosen. Prior studies generally choose a current that ranges from 0.1 mA up to 2.0 mA, though some studies have used currents of up to 4.0 mA (e.g. in stroke patients; Chhatbar et al., 2017). However, generally anything above 2.0 mA raises concern for the participant. The amount of current in the present study was not maximal and could be the reason for mostly null effects. In addition, in a metanalytic review by Hill, Fitzgerald, and Hoy (2016), these researchers argue that a current below 1.0 mA does not have much effect on various outcome measures whereas higher currents do have a larger effect. Furthermore, the amount of current that reaches the brain region of interest is not necessarily maximal. Miranda, Lomarev, and Hallett (2006) found that when using 2.0 mA of stimulation, a reduced amount actually reaches the area of interest. They estimate that about half of the current is lost through the dura mater of the scalp as well as through cerebral spinal fluid. While it is not possible in the present study to estimate the spread of the current or the reduction in current that occurred, future research may consider these barriers when deciding on placement of electrodes and the amount of current used. In addition, the type of electrode used may help in enhancing the focus of stimulation to gain maximal effect (Bortoletto, Rodella, Salvador, Miranda, & Miniussi, 2016).

The LTM task was originally added to this project as an exploratory measure to investigate whether effects of tDCS might extend beyond WM. Since this aspect of the study was not the primary focus, the experimental design was limited. While stimuli were properly counterbalanced in the WM tasks, this was neglected in the LTM task. Thus, the order of the stimuli presented could have created a confounding effect such as the order of presentation (order effects). Since there was a trend in the tDCS stimulation condition when assessing LTM task accuracy, future research should consider the design of the study carefully with proper counterbalancing of stimuli. In addition, future research may want to assess LTM at different time points (i.e. short delay, one-day delay, one-week delay, etc.).

The prominent Baddeley and Hitch (1974) WM model is one of several proposed working memory models. For example, the Embedded-Process Model places greater emphasis on underlying cognitive processes that occur when solving a task (Cowan, 1988). Others emphasize the importance of inhibitory processes, which may be crucial to shielding the memory content from disruption (Engle, Tuholski, Laughlin, & Conway, 1999; Engle & Kane, 2004) as well as focusing on specific anatomical locations of memory (Jonides et al., 2008). These theories, however, tend to be too narrow in scope and have many exceptions. At the time of writing, the Baddeley and Hitch (1974) model appears to be the most succinct and empirically sound, though future research may want to explore this topic in context of other models.

The literature surrounding non-invasive brain stimulation is mixed and continues to be. The use of tDCS seemed to have a slightly opposite effect on memory when comparing WM to LTM. In addition, when comparing to control conditions, this study failed to find any significant difference in accuracy and reaction times. This paradoxical finding illustrates the need for more research in both the WM and non-invasive brain stimulation fields both together and separately.

REFERENCES

Albouy, P., Benjamin, L., Morillon, B., & Zatorre, R. J. (2020). Distinct sensitivity to spectrotemporal modulation supports brain asymmetry for speech and melody. *Science, 367*(6481), 1043-1047. DOI: 10.1126/science.aaz3468

Albouy, P., Peretz, I., Bermudez, P., Zatorre, R. J., Tillmann, B., & Caclin, A. (2018). Specialized neural dynamics for verbal and tonal memory: fMRI evidence in congenital amusia. *Human Brain Mapping, 40*(3), 855-867. DOI: 10.1002/hbm.24416

Antal A., Nitsche, M. A., Kruse, W., Kincses, T. Z., Hoffmann, K-P., Paulus, W. (2004). Direct current stimulation over V5 enhances visuomotor coordination by improving motion perception in humans. *Journal of Cognitive Neuroscience, 16*(4), 521-527. DOI: 10.1162/089892904323057263

Ardolino, G., Bossi, B., Barbieri, S., & Priori, A. (2005). Non-synaptic mechanisms underlie the after-effects of cathodal transcutaneous direct current stimulation of the human brain. *The Journal of Physiology, 568*(Pt 2), 653–66 3.

Atkinson, R. C., & Shiffrin, R. M. (1968). Human Memory: A proposed system and its control processes. In K. W. Spence & J. T. Spence (Eds.) *The Psychology of Learning and Motivation: II*. Oxford: Academic Press. DOI: 10.1016/S0079-7421(08)60422-3

Boros, K., Poreisz, C., Munchau, A., Paulus, W., & Nitsche, M. A. (2008). Premotor transcranial direct current stimulation (tDCS) affects primary motor excitability in humans. *The European Journal of Neuroscience, 27*(5), 1292–1300.

Baddeley, A. (2000). The episodic buffer: a new component of working memory? *Trends in Cognitive Science, 4*(11), 417-423. DOI: 10.1016/S1364-6613(00)01538-2

Baddeley, A., and Hitch, G. (1974). Working Memory. In G. H. Bower (Ed.), *The Psychology of Learning and Motivation, Vol. 8* (pp. 47-89). New York: Academic Press.

Baddeley, A., Lewis, V., & Vallar, G. (1984). Exploring the articulatory loop. *Quarterly Journal of Experimental Psychology, 36*(2), 233-252. DOI: 10.1080/14640748408402157

Berz, W. (1995). Working memory in music: a theoretical model. *Music Perception, 12*(3), 353-364. DOI: 10.2307/40286188

Boehringer, A., Macher, K., Dukart, J., Villringer, A., & Pleger, B. (2013). Cerebellar transcranial direct current stimulation modulates verbal working memory. *Brain Stimulation, 6*(4).

Bortoletto, M., Rodella, C., Salvador R., Miranda, P.C., & Miniussi, C. (2016). Reduced current spread by concentric electrodes in transcranial electrical stimulation (tES). *Brain Stimulation, 9*(4), 525-528. DOI: 10.1016/j.brs.2016.03.001

Cohen, J. (1988). Statistical Power Analysis for the Behavioral Sciences. New York, NY: Routledge Academic.

Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. *Psychological Bulletin, 104*(2), 163-191. DOI: 10.1037/0033-2909.104.2.163

Craik, F. I. M. & Bialystok, E. (2006). Cognition through the lifespan: Mechanisms of change. *Trends in Cognitive Sciences, 10*(3), 131-138. DOI: 10.1016/j.tics.2006.01.007

DaSilva, A. F., Volz, M. S., Bikson, M., & Fregni, F. (2011). Electrode positioning and Montage in Transcranial Direct Current Stimulation. *Journal of Visualized Experiments, 51*. DOI: 10.3791/2744

Engle, R. W., & Kane, M. J. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. In B. Ross (Ed.), The Psychology of Learning and Motivation, Vol. 44. New York, NJ: Elsevier.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General, 128*(3), 309-331. DOI: 10.1037/0096-3445.128.3.309

Finch, A., Stern, M. J., Deason, R. G. (2019, October). Music enhances source memory and confidence for novel verbal information. Poster presentation given at the 27th annual ARMADILLO conference for cognition and cognitive science, San Antonio, TX.

Flegal, K. E., Ragland, J. D., & Ranganath, C. (2019). Adaptive task difficulty influences neural plasticity and transfer of training. *NeuroImage, 188*, 111-121. DOI: 10.1016/j.neuroimage.2018.12.003

Hantz, E. C., Marvin, E. W., Kredilick, K. G., & Chapman, R. M. (1996). Sex differences in memory for timbre: An event-related potential study. *International Journal of Neuroscience, 87*(1-2), 17-40. DOI: 10.3109/00207459608990751

Hill, A. T., Fitzgerald, P. B., & Hoy, K. E. (2016). Effects of anodal transcranial direct current stimulation on working memory: A systematic review and meta-analysis of findings from healthy and neuropsychiatric populations. *Brain Stimulation*, *9*(2), 197–208. DOI: 10.1016/j.brs.2015.10.006

Hovarth, J. C., Carter, O., & Forte, J. D. (2014). Transcranial direct current stimulation: five important issues we aren't discussing (but portably should be). *Frontiers in Systems Neuroscience, 8*(2). DOI: 10.3389/fnsys.2014.00002.

Inukai, Y., Saito, K., Sasaki, R., Tsuiki, S., Miyaguchi, S., Kojima, S., . . . Onishi, H. (2016). Comparison of three non-invasive transcranial electrical stimulation methods for increasing cortical excitability. *Frontiers in Human Neuroscience, 10*(668). DOI: 10.3389/fnhum.2016.00668

Ivanova, M. V., Dragoy, O., Kuptsova, S. V., Akinina, S. Y., Petrushevskii, A. G., Fedina, O. N., … Dronkers, N. F. (2018). Neural mechanisms of two different verbal working memory tasks: A VLSM study. *Neuropsychologia, 115*, 25–41. DOI: 10.1016/j.neuropsychologia.2018.03.003

Javadi, A. H & Cheng, P. (2013). Transcranial Direct Current Stimulation (tDCS) Enhances Reconsolidation of Long-Term Memory. *Science, 6*(4), 668-674. DOI: 10.1016/j.brs.2012.10.007

Jones, K. T., Gozenman, F., & Berryhill, M. (2014). Enhanced long-term memory encoding after parietal neurostimulation. *Experimental Brain Research, 232*(12), 4043-4054. DOI: 10.1007/s00221-014-4090-y

Jonides, J., Lewis, R. L., Nee, D. E., Lustig, C. A., Berman, M. G., & Moore, K. S. (2008). The mind and brain of short-term memory. *Annual Review of Psychology, 59*(1), 192-224. DOI: 10.1146/annurev.psych.59.103006.093615

Kelemen, W. L. (2000). Metamemory cues and monitoring accuracy: Judging what you know and what you will know. *Journal of Educational Psychology*, (4), 800, doi: 10.1037/0022-0663.92.4.800

Kyongje, S. & Gordon, B. (2018). Transcranial direct current stimulation (tDCS) facilitates overall visual search response times but does not interact with visual search task factors. *PLoS One, 13*(3).

Loftus, E. F. & Palmer, J. C. (1974). Reconstruction of automobile destruction: An example of the interaction between language and memory. *Journal of Verbal Learning and Verbal Behavior, 13*(5), 585-589. DOI: 10.1016/S0022-5371(74)80011-3

Matsumoto, H. & Ugawa, Y. (2017). Adverse events of tDCS and tACS: A review. *Clinical Neurophysiology Practice, 2*, 19-25. DOI: 10.1016/j.cnp.2016.12.003

Medina, J. & Cason, S. (2017). No evidential value in samples of transcranial direct current sitmulation (tDCS) studies of cognition and working memory in healthy populations. *Cortex, 94*, 131-141. DOI: 10.1016/j.cortex.2017.06.021

Merrill, D. R., Bikson, M., & Jeffereys J. G.R. (2005). Electrical stimulation of excitable tissue: design of efficacious and safe protocols. *Journal of Neuroscience Methods, 141*(2), 171-198. DOI: 10.1016/j.jneumeth.2004.10.020

Miranda, P. C., Lomarev, M, & Hallett, M. (2006). Modeling the current distribution during transcranial direct current stimulation. *Clinical Neurophysiology, 117*(7), 1623-1629. DOI: 10.1016/j.clinph.2006.04.009

Monai, H. & Hirase, H. (2018). Astrocytes as a target of transcranial direct current stimulation (tDCS) to treat depression. *Neuroscience Research, 126*, 15-21. DOI: 10.1016/j.neures.2017.08.012

Moreno-Durante, I., Gebodh, N., Schestasky, P., Guleyupoglu, B., Reato, D., Bikson, M., & Frengi, F. (2014). The stimulated brain: Cognitive enhancement using non-invasive brain stimulation. San Diego, CA: Academic Press.

Müllensiefen, D., Gingras, B., Musil, J., & Stewart L. (2014). The musicality of non-musicians: an index for assessing musical sophistication in the general population. *PLoS ONE, 9*(2). doi:10.1371/journal.pone.0089642

Nitsche, M. A., Fricke, K., Henschke, U., Schillterlau, A., Liebetanz, D., Lang, N., et al. (2003). Pharmological modulation of cortical excitability shifts induced by transcranial direct current stimulation in humans. *The Journal of Physiology, 553*, 293-301.

Rogalewski, A., Breitenstein, C., Nitsche, M. A., Paulus, W., & Knecht, S. (2004). Transcranial direct current stimulation disrupts tactile perception. *European Journal of Neuroscience, 20*(1), 313-316. DOI: 10.1111/j.0953-816X.2004.03450.x

Sares, A. G., Foster, N. E. V., Allen, K., & Hyde, K. L. (2018). Pitch and time processing in speech and tones: The effects of musical training and attention. *Journal of Speech, Language, and Hearing Research, 61*(3), 496-509. DOI: 10.1044/2017_JSLHR-S-17-0207

Schaal, N.K., Karuse, V., Lange, K., Banissy, M.J, Williamson, V.J., & Pollok, V. (2015). Pitch memory in nonmusicians and musicians: revealing functional differences using transcranial direct current stimulation. *Cerebral Cortex, 25*(9), 2774-2782. DOI: 10.1093/cercor/bhu075

Schwippel, T., Papazova, I., Strube, W., Fallgatter, A. J., Hasan, A. & Plewnia, C. (2018). Beneficial effects of anodal transcranial direct current stimulation (tDCS) on spatial working memory in patients with schizophrenia. *European Neuropsychopharmacology*. DOI: 10.1016/j.euroneuro.2018.09.009

Schulze, K. & Tillmann, B. (2013). Working memory for pitch, timbre, and words. *Memory, 21*(3), 77-95. DOI: 10.1080/09658211.2012.731070

Squire, L. R. (1987). Memory and brain. Oxford University Press.

Talsma, L. J., Kroese, H. A., & Slagter, H. A. (2017). Boosting cognition: Effects of multiple-session transcranial direct current stimulation on working memory. *Journal of Cognitive Neuroscience*, *29*(4), 755–768. DOI: 10.1162/jocn_a_01077

Tulving, E. (1989). Memory: performance, knowledge, and experience. *European Journal of Cognitive Psychology, 1*(1), 3-26. DOI: 10.1080/09541448908403069

Vines, B., Schnider, N. M., & Schlaug, G. (2006). Testing for causality with transcranial direct current stimulation: Pitch memory and the left supramarginal gyrus. *NeuroReport: For Rapid Communication of Neuroscience Research, 17*(10), 1047-1050. DOI: 10.1097/01.wnr.0000223396.05070.a2

Vogel, R. W. (2017). Understanding anodal and cathodal stimulation. Retrieved from https://www.asnm.org/blogpost/1635804/290597/Understanding-Anodal-and-Cathodal-Stimulation

Vöröslakos, M., Takeuchi, Y., Brinyiczki, K., Zombori, T., Oliva, A., Fernández-Ruiz, A., . . . Berényi, A. (2018). Direct effects of transcranial electric stimulation on brain circuits in rats and humans. *Nature Communications, 4*(483). DOI: 10.1038/s41467-018-02928-3

Williamson, V. J., Baddeley, A. D., & Hitch, G. J. (2010). Musicians' and nonmusicians' short-term memory for verbal and musical sequences: Comparing phonological similarity and pitch proximity. *Memory and Cognition, 38*(2), 163-175. DOI: 10.3758/MC.38.2.163