Effects of Transcranial Stimulation on Memory for Social Information in Younger and Older Adults

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THESIS

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This thesis is dedicated to my lovely wife, Elizabeth Wontor-Leach, who exemplifies how to seize each day and never ceases to amaze me.

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LIST OF ABBREVIATIONS

AUC	Area Under the Curve
dlPFC	Dorsolateral Prefrontal Cortex
ERP	Event Related Potential
FA	False Alarm
fMRI	Functional Magnetic Resonance Imaging
IFG	Inferior Frontal Gyrus
LTP	Long-Term Potentiation
NMDA	N-methyl-D-aspartate
PFC	Prefrontal Cortex
ROC	Receiver Operating Characteristics
tDCS	Transcranial Direct Current Stimulation
WMC	Working Memory Capacity

SUMMARY

Episodic memory decline is a normal and expected part of the aging process. However, not all types of memory show equal decline throughout the lifespan. Older adults experience deficits in the ability to remember associations between items over and above the ability to remember the items themselves (Spencer & Raz, 1995). In this study, I tested a novel technique to improve associative memory in older adults, transcranial direct current stimulation (tDCS). Stimulation was applied while participants studied face-name pairs, and participants then completed both cued recall and recognition tests. In addition to testing the beneficial effects of tDCS, several other parameters were tested. This included the generalizability of tDCS to other populations (i.e., younger adults), the difference in magnitude of tDCS effects depending upon the number of trial repetitions during encoding, and whether the effects would last after a delay. Results indicated that stimulation was effective in improving face-name associative memory performance, but only for younger adults. Multiple presentations of stimuli during a stimulated encoding session did not have an effect on tDCS impact. Effects of tDCS did persist 24 hours later in the younger adult sample, but this effect did not go above and beyond the effects on memory measured on the first day, suggesting that this result was simply a carry-over effect from enhanced performance on the first day. Taken together, results indicate that tDCS changes behavioral performance in certain populations, and that effects persist after a short delay.

Introduction

Most people would recognize country music legend Glen Campbell by his biggest hits, “Rhinestone Cowboy” and “Wichita Lineman.” These were included among the many popular songs written during his illustrious career. Unfortunately, this beloved musician was diagnosed with Alzheimer’s disease in 2011. After learning of his diagnosis, he wrote and recorded his final tragically named song, called “I’m Not Going to Miss You,” as a goodbye to his wife. Lyrics such as “I'm never gonna (sic) hold you like I did / Or say I love you to the kids / You're never gonna see it in my eyes / It's not gonna hurt me when you cry / I'm never gonna know what you go through / All the things I say or do / All the hurt and all the pain / One thing selfishly remains” give blunt testimony to the importance of memory to daily life (Campbell & Raymond, 2014, Track 1). In fact, these words foreshadowed actual events, as Glen Campbell, forced to live in an Alzheimer’s treatment facility, became unable to hold a conversation and could not understand and appreciate when a movie based on his last album won an Academy Award. Alzheimer’s disease is an extreme example of memory loss, however, non-clinical decline of memory processes is very common in older adults (e.g., Light 1991) and distressing (e.g., Jonker, Geerlings, & Schmand, 2000). Thus, the purpose of this study is to test one possible way to bolster memory in older adults.

A common type of memory decline is losses in ability to remember the name of an acquaintance. Failure to retrieve names in communication could result in confusion and embarrassment, and even cause offense (Cohen, 1994). Unfortunately, older adults show declines in the ability to remember names (Cohen, & Faulkner, 1986; Rendell, Castel, & Craik, 2005), and especially the associations of names with faces (Naveh-Benjamin, Guez, Kilb, & Reedy, 2004). The inability to remember names of close friends and family is a common yet

distressing outcome for older adults (Maylor, 1997). The issue of memory decline will only become more intense in this country, as the proportion of the population aged 65 and older is projected to increase from approximately 15% in 2014 to nearly 24% in 2060, when the older adult population it expected to be more than double the current figure (U.S. Census Bureau, 2014). Thus, the current work will examine the efficacy of a novel method of non-invasive brain stimulation, called transcranial direct current stimulation (tDCS), on improving face-name association memory in older adults.

Before laying out the current study, I will begin by providing background information important to age-related cognitive decline and previous uses of tDCS. I will first explain the decline of episodic memory ability in older adults, and how certain types of memory ability (i.e., memory for associations) decline more than others. I will describe associative memory deficits, including historical context behind the use of the term associative memory to describe this deficit, and psychological and neuroscientific reasons for the decline in associative memory performance (See **Episodic Memory Decline in Older Adults)**.

Next, I will turn to work with tDCS on older adults and explain past uses of the technique in that population, with a specific focus on work exploring the effects of tDCS on memory. Work with tDCS on memory has also included younger adults, and I will describe that work to justify the use of a younger adult comparison group in the current study. This literature will be used to support my main hypothesis that tDCS will improve memory in younger and older adults. I will then explain two other hypotheses I make in the current work: first, that a greater amount of stimulation during study will result in greater effects of the stimulation (i.e., scaling effects of stimulation), and second, that the effects of stimulation will still be present one day after the

initial stimulation procedure (i.e., timing effects of stimulation; See **Transcranial Direct Current Stimulation)**.

Finally, as most neuroscientific evidence on associative memory in older adults focuses on neuroimaging, the vast majority of the literature showing a link between brain activity and associative memory is based on correlational evidence. This work would be one of the first to show a causal link from brain activity to associative memory performance with an experimental design. That is, because this study will involve a direct manipulation of brain activity, any changes to memory performance will only be attributable to the manipulation. I will return to this issue in the discussion.

Episodic Memory Decline in Older Adults

I will now discuss relevant work on memory loss in older adults, and provide historical background on why I use the term associative memory to describe these deficits. I will then turn to past research that lays out both psychological and neuroscientific reasons behind these memory declines in older adults. Thus in this section, I will explain the basic problem to be solved with tDCS.

Cognitive decline, including reductions in memory, typically accompanies advancing age (Light, 1991; Park, 2000). Changes in memory ability can range from mere annoyances which spur common complaints about day-to-day memory performance (Jonker et al., 2000; Leirer, Morrow, Sheikh, & Pariante, 1990; Reese, Cherry, & Norris, 1999; Reid & MacLullich, 2006), to heartbreaking catastrophes, as with the events in Glen Campbell's life.

Although memory decline is prevalent in older populations, there is a particular aspect of memory that shows the steepest decline: older adults show poorer memory for *associations* between stimuli (i.e., *associative memory*) than for the actual stimuli themselves (i.e., item

memory; Naveh-Benjamin, 2000; Old & Naveh-Benjamin, 2008a; Spencer & Raz, 1995). Decline in memory for associations in older adults has been named the *associative memory deficit* (Naveh-Benjamin, 2000; also see Kausler, 1994). As an everyday example, older adults have trouble remembering names of people they meet, but suffer more intensely from deficits to the associations between names and faces (Cohen, & Faulkner, 1986; Rendell et al., 2005; Naveh-Benjamin et al., 2004). In laboratory procedures, this type of memory is referred to as *face-name association memory* (i.e., remembering that *this* face goes with *that* name). As previously stated, the specific deficit in face-name association memory will be the focus for the current work.

Evidence for the associative-memory deficit. Early evidence of an associative deficit showed that older adults perform worse than younger adults[1] when attempting to remember whether words were presented in upper or lower case (Kausler & Puckett, 1980) or whether information was spoken by a male or female (Kausler & Puckett, 1981; i.e., remembering that *this* item was spoken by *that* speaker). Interestingly, older adults showed less of a deficit for the words themselves (i.e., item memory), and this raised the possibility that older adults suffer from specific *context memory deficits*, or deficits in remembering the context in which memories were encoded.

Further research uncovered the same pattern in many different manifestations, and set the stage for later theorization that combined each manifestation into a singular associative-memory paradigm. Context memory deficits include an inability to remember the temporal order information was presented in (Kausler & Wiley, 1990; Spencer & Raz, 1994), the color of items when presented (Park & Puglisi, 1985), or the spatial location of information (Denney et al., 1992; Evans et al., 1984; Hess & Slaughter, 1990; Park, Puglisi, & Lutz, 1982; Park, Puglisi, &

[1] An important note: deficits with older adults are always defined relative to younger-adult performance.

Sovacool, 1983; Puglisi, Park, Smith, & Hill, 1985; Zeilinski & Light, 1988) more than the inability to remember the information itself. A related paradigm is called *reality monitoring*, in which participants are asked to differentiate words that they had read versus those they had previously generated (Johnson & Raye, 1981). Using this paradigm, older adults show a more moderate deficit for the words themselves compared to the large deficit found when differentiating context (Cohen & Faulkner, 1989; Rabinowitz, 1989, Experiment 2). Similar results are found when asking participants whether a word was presented in an auditory or visual modality (i.e., a *modality identification*; Lehman & Mellinger, 1986; Light, La Voie, Valencia-Laver, Albertson-Owens, & Mead, 1992; Mellinger, Lehman, Happ, Grout, 1990). A final type of deficit older adults show to a greater degree than item-memory deficits are *source memory* deficits, in which participants must remember information about the source of stimuli, such as from which speaker a word was presented (Ferguson, Hashtroudi, & Johnson, 1992; Hashtroudi, Johnson, Vnet, & Ferguson, 1994; Johnson et al., 1995; Schacter, Kasznaik, Kihlstrom, & Valdiserri, 1991; Schacter, Osowiecki, Kasznaik, Kihlstrom, & Valdiserri, 1994). These early studies were summarized in a meta-analysis which determined that across all of the literature, aging had a larger effect on context memory than memory for content (Spencer & Raz, 1995). More recent research published since has corroborated older adults' deficits in contextual information (such as the specific list a stimulus originated from; Bastin & Van der Linden, 2005, Experiment 2; Lipman, 1991; Luber et al., 2004; Parkin et al., 1995; Trott et al., 1997, 1999; Wegesin et al., 2000, 2002; spatial location of stimuli; Bastin & Van der Linden, 2005; Lyle et al., 2006; or temporal order of stimuli; Dumas & Hartman, 2003; Newman et al., 2001; Schmitter-Edgecombe & Simpson, 2001; Wilkniss et al., 1997) and source information (Brown et al., 1995; Frieske & Park, 1999; Glisky et al., 2001; Mather et al., 1999; Naveh-Benjamin &

Craik, 1995, Experiment 2; Simons et al., 2004) over deficits for item memory relative to younger adults. These deficits became known as *associative deficits*.

The term *associative deficit* is now used as a catch-all term to describe memory deficits in older adults that include context memory deficits, source memory deficits, and deficits in reality monitoring and modality identification (Naveh-Benjamin, 2000). This paradigm explains deficits in terms of concrete associations, instead of the more-vague "contexts."

The associative deficit hypothesis also incorporates item-pair retrieval (e.g., Naveh-Benjamin, 2000), which cannot be categorized as context or source memory yet is associative in nature. For instance, older adults show smaller deficits relative to younger adults for words, nonwords, and fonts than for associations between word-nonword pairs, word-font pairs, or word-word pairs (Naveh-Benjamin, 2000; Naveh-Benjamin & Craik, 1995, Experiment 1; Naveh-Benjamin, Guez, & Shulman, 2004; Naveh-Benjamin, Hussain, Guez, & Bar-On, 2003, Experiment 2). The same pattern holds for picture pairs (Naveh-Benjamin et al., 2003, Experiment 1), person-action pairs (Old & Naveh-Benjamin, 2008b), and, importantly to the current work, face-name pairs (Naveh-Benjamin et al., 2004; see Old & Naveh-Benjamin, 2008a). Finally, some of the strongest evidence to date for the associative deficit hypothesis came from research incorporating a sample of people from across the entire lifespan, showing clear evidence of gradual associative decline with increasing age (Bender, Naveh-Benjamin, & Raz, 2010).

This work was carried out using measures called *paired-associate memory tasks* (Glenberg & Bradley, 1979; Humphreys, 1976). As an example, previous researchers have used this technique with face-name pairs (each face presented with a name). After encoding these pairs, participants saw a face that was paired with either the same name that it was paired with

during the encoding session or a name that was paired with a different face during the encoding session (Naveh-Benjamin et al., 2004). Thus, recognition for the face-name *association* was tested, and not recognition for individual faces or names. This procedure has been widely used for many types of associations, such as pairs of unrelated words (Naveh-Benjamin, 2000) or images (Naveh-Benjamin et al., 2003). I will use this procedure in the current study.

Cognitive deficits associated with the associative-memory deficit. The associative deficit hypothesis describes the phenomenon, but other researchers have attempted to explain why these deficits occur. These include older adults' use of sub-optimal memory strategies and neural deficiencies related to the binding of multiple units of information together as a single association. I will now review evidence for these possible mechanisms.

Uses of strategy. One possible mechanism of older adults' underperformance on tests of associative memory is a deficit in impromptu use of appropriate encoding strategies relative to younger adults. Indeed, the use of poor strategies at encoding can lead to poorer memory (Lachman & Andreoletti, 2006). It is possible to improve memory in older adults by instructing all participants in a study in the use of memory strategies (e.g., Ball et al., 2002; Cherry, Simmons, & Camp, 1999; Cohn, Emrich, & Moscovitch, 2008; Dunlosky, Kubat-Silman, & Hertzog, 2003; Jennings, Webster, Kleykamp, & Dagenbach, 2005; Naveh-Benjamin, Brav, & Levy, 2007), and although this reduces differences in performance between younger and older adult, age-related deficits are not abolished (e.g., Dunlosky & Hertzog, 1998; Naveh-Benjamin, Craik, Guez, & Kreuger, 2005). The current study instructs participants in learning strategy in order to ensure similarities in encoding technique across age group. This establishes that differences in memory performance between older and younger adults are not simply due to differences in task strategy.

Binding deficit. The ability to encode an association between two items as a single representation in memory, a process known as binding, also declines due to aging. Binding is argued to result from hippocampal function (Cohen et al., 1999; Olsen et al., 2012), and while older adults may show memory deficits for contextual features themselves (such as the location in an array, color, or size), they show a greater memory deficit for the binding between features, or the association between item and contextual features (Chalfonte and Johnson, 1996; Kessels, Hobbel, & Postma, 2007), reflecting modest hippocampal decline (Rosenzweig & Barnes, 2003; West, 1993). Although this result could simply be due to an increased test load (i.e., memory for two features/items instead of one; Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000), older adults show less of an associative deficit for semantically related word pairs relative to semantically-unrelated word pairs (Naveh-Benjamin et al., 2003, experiment 2), showing that the deficit in older adults is at least partly due to the difficulty in forming new associations. Because the purpose of this work is to explore the potential for brain stimulation to improve this ability in older adults, research on brain mechanisms supporting binding, and those behind the binding deficit, inform the proposed experiment.

Hippocampal involvement in binding. Several brain regions show activity during associative tasks in younger adults but also show decline due to age. For younger adults, activation in the hippocampus, a brain area associated with the formation of new memories, is found during associative memory tasks (Henke, Buck, Weber, & Wieser, 1997). Hippocampal involvement in associative memory has also been found with object-location (Mitchell et al., 2000) and face-name associative encoding (Sperling et al., 2001). Furthermore, hippocampal activity during encoding is correlated with enhanced association-memory accuracy for word pairs (Jackson & Schacter, 2004) and face-name associations (Sperling et al., 2003) in younger

adults. Older adults, however, do not show the same pattern of increased hippocampal activity during associative encoding (Chee et al., 2006; Mitchell et al., 2000), suggesting that older adults' deficit in associative memory stems from under-recruitment of the hippocampus.

In summary, it appears that declines in hippocampal function are partly responsible for the associative memory deficit in older adults. However, important to the current study, there are other areas that may be important for associative memory, namely, the prefrontal cortex (PFC). Prior work suggests that prefrontal areas are connected with the hippocampus (e.g., Grady, McIntosh, & Craik, 2003) and play an additional role in associative memory, such as the generation of associations that are then bound by the hippocampus (Addis & McAndrews, 2006). Additional work suggests that the PFC is more susceptible to age related decline than other areas (West, 1996).

Frontal aging hypothesis. A key assumption of the frontal aging hypothesis is that declines in frontal lobe function mediates cognitive decline in older adults (see West, 1996 for a review). According to this view, older adults are particularly impaired for tasks of memory because of decreased neural function of the PFC (Hedden & Gabrieli, 2004). Activity in the PFC has been linked to associative memory performance by many different lines of research, using behavioral, ERP, and fMRI data. Additionally, younger adults with lesions to frontal areas resemble older adults in associative memory task performance (Janowsky, Shimamura, & Squire, 1989; Moscovitch & Melo, 1997; Shimamura, Janowsky, & Squire, 1990, Swick, Senkfor, & Van Petten, 2006). Behaviorally, tasks that have been found to correlate with individual difference in prefrontal grey matter volume (i.e., Wisconsin Card Sorting Task, verbal fluency, mental arithmetic, mental control, and backward digit span) also associate closely with measures of associative memory (Craik, Morris, Morris, & Loewen, 1990; Glisky, Polster, & Routhieaux,

1995; Schacter et al., 1991; Spencer & Raz, 1994). Older adults score lower on many of these frontal tasks (Daum, Gräber, Schugens, & Mayes, 1996), suggesting that function of PFC is related to performance on associative memory tasks.

Another line of evidence for the frontal aging hypothesis comes from work with event-related potentials (ERP). This research reveals a close relationship between activation of prefrontal regions when younger adult participants decide whether a word was associated with a male or female voice (Senkfor & Van Petten, 1998; Swick et al., 2006; Wilding, & Rugg, 1996), with a perceived picture or imagined picture (Johansson, Stenberg, Lindgren, & Rosén, 2002), with a certain temporal order (Trott, Friedman, Ritter, & Fabiani, 1997), a certain list (i.e., subset) of stimuli (Trott, Friedman, Ritter, Fabiani, & Snodgrass, 1999; Wegesin et al., 2002), or visual or auditory presentation (Wilding, Doyle, & Rugg, 1995). Older adults, however, underperform on these types of associative tasks and show a diminished prefrontal ERP response during associative judgments (Trott et al., 1997, 1999; Wegesin et al., 2002), similar to frontal lesion patients (Swick et al., 2006). The PFC is also involved when participants remember the locations of drawings (Van Petten, Senkfor, & Newberg, 2000), and importantly, with face-name association memory (Goffaux, Jemel, Jacques, Rossion, & Schyns, 2003). The prefrontal ERP effect disappears with greater integration of the to-be associated stimuli, showing that PFC is important when associations must be generated (Kuo, & Van Petten, 2006).

Work with ERP does merit a brief caveat, however. Because of the difficulty with pinpointing ERP's to specific brain regions, all this evidence should be considered in conjunction with evidence from other brain imaging techniques. Fortunately, recent work has investigated prefrontal contributions to associative memory with functional magnetic resonance imaging (fMRI).

A large amount of research using fMRI has implicated the left PFC in tasks of associative memory when contrasted with brain activity during item memory tasks in younger adults (see Mitchell & Johnson, 2009, for a review). Specifically, the left dorsolateral PFC (dlPFC) is more active during associative encoding than during item encoding, and is correlated to later associative memory performance but not item memory performance (Murray & Ranganath, 2007). However, this is not the case for older adults, who do not show the same activation differential between item and associative memory (Mitchell, Raye, Johnson, & Greene, 2006), and this activation pattern correlates with decreased performance on associative-memory tasks (Dennis, Hayes, Prince, Madden, Huettel, & Cabeza, 2008). Finally, activity in the PFC correlates highly with activity in the hippocampus during associative encoding, indicating a functional connection (Addis & McAndrews, 2006).

Taken together, these results show that PFC and hippocampal areas function together to support associative memory. Any intervention aimed at improving associative memory in older adults must take into account the biological factors mediating this decline. Thus, the current study will target a subregion of the PFC important for associative memory performance (i.e., dlPFC; Murray & Ranganath, 2007). This area will be stimulated using transcranial direct-current stimulation (tDCS), a non-invasive brain stimulation technique that has gained recent interest in improving cognition in younger adults, older adults, and those with cognitive disabilities. I will discuss previous research with tDCS in the next section.

Can Associative Memory be Improved in Older Adults?

To improve various forms of cognition and motor function in older adults, novel procedures of directly modulating brain function has become increasingly popular. Collectively known as brain stimulation, these procedures include deep brain stimulation, transcranial

magnetic stimulation, and tDCS, among others. These procedures use biological, rather than cognitive, pathways to improve cognition and have the potential to enhance cognitive ability without the use of training protocols. In the next section, I will outline how tDCS functions, and will present past research findings on the cognitive benefits of tDCS with older adults. I will also present research on the effects of tDCS on memory in younger adults, justifying the use of a younger-adult comparison group in the current study. Although the primary purpose of this study is to test the effectiveness of tDCS in improving face-name memory performance, I will explain two further hypotheses in the current study: that a greater amount of stimulation will lead to greater effects, and that the effects of tDCS will still be present when tested one day after the initial stimulation session.

Transcranial Direct-Current Stimulation

tDCS is safe, noninvasive, inexpensive, and is effective in improving cognitive ability of various types (for a review, see Coffman, Clark, & Parasuraman, 2014). tDCS sends a slight electrical current through the scalp to modulate the resting potential of cortical neurons, making neurons more or less likely to fire (Nitsche & Paulus, 2000). Specifically, when electrodes are placed on the scalp above the targeted cortical region, stimulation from the anodal (positively charged) electrode is known to alter the function of stimulated neurons. Active stimulation is usually compared to sham stimulation, a control condition in which current is applied at a fraction of the active current (e.g., Clark et al., 2012). For this study, I compared participants who received anodal stimulation with those that received sham stimulation.

There are two proposed mechanisms by which tDCS affects cognition (Stagg & Nitsche, 2011). *Online effects*, or effects that occur during the stimulation interval, are thought to be mediated by the immediate effects of stimulation on neuronal membranes. That is, online effects

are apparent during or immediately after the stimulation period, and reflect changes in neuronal firing rates (Scholfield, 1990; Stagg & Nitsche, 2011) *Offline effects*, or after effects, on the other hand, linger after the stimulation period has ended. For instance, motor sequence performance was greater for older adults that had received anodal tDCS rather than sham stimulation even 24 hours after the stimulation (e.g., Zimerman et al., 2013). On the extreme end of this spectrum, 6 days of training concurrently paired with tDCS produced an improvement in numerical proficiency compared to sham performance in younger adults that was apparent when tested 6 months after the initial training session (Kadosh, Soskic, Iuculano, Kanai, & Walsh, 2010). Offline effects also operate through different mechanisms than online effects. Long-term potentiation (LTP) is a process by which the connections between neurons become stronger after a network is activated, and offline effects are thought to engage a similar process (i.e., LTP processes rely upon NMDA receptors, and blocking those receptors abolishes offline effects but not online effects; Liebetanz, Nitsche, Tergau, & Paulus, 2002; Nitsche et al., 2003, 2004; Stagg & Nitsche, 2011). When improving cognitive capacity in older adults, tDCS ostensibly operates via both online and offline mechanisms, and both mechanisms were tested in the current study.

tDCS with older adults. Recent research has shown that applying tDCS can improve various aspects of cognition in older adults, including motor function (e.g., Hardwick & Celnick, 2014; Wegscheider, Rumpf, Fricke, Weise, & Classen, 2013), verbal fluency (e.g., Fertonani, Brambilla, Cotelli, & Miniussi, 2014; Meinzer, Lindenberg, Antonenko, Flaisch, & Flöel, 2013), error awareness (Harty et al., 2014), and working memory (see Teixeira-Santos, Nafee, Sampaio, Leite, & Carvalho, 2015 for a review). I will review this work in the next section to provide an overview of how tDCS can be used to influence function in older adults.

Motor function. As individuals age, they experience declines in motor function, including reduced coordination (Sarlegna, 2006) and slowed movement initiation (Bennett & Castiello, 1994). Numerous recent studies have found that tDCS can increase motor function on several different motor tasks. For example, tDCS stimulation applied over the left primary motor cortex hand area increased physical dexterity for several tasks involving fine motor movement and coordination (Parikh & Cole, 2014), with these performance gains lasting after the session, showcasing the offline effects of tDCS. Application to the same region reduced costs associated with dual tasking- that is, walking or standing while performing serial subtractions (Manor et al., 2015; Zhou et al., 2015). These findings show the efficacy of tDCS in the improvement of functions that show normal age-related decline in older adults. The ability to initiate lasting change of motor function also displays the offline effects of tDCS.

Tasks of motor adaptation test the ability to subtly adapt one's movements, a vital skill for motor control. In one study, participants completed a reaching task, during which an obstacle was introduced. Older adults that received tDCS were able to adapt to the obstacle with fewer errors than were older adults without the stimulation. The authors found that stimulation of the cerebellum in older adults decreased errors on this task to the level of younger adult performance (Hardwick & Celnick, 2014). In a different adaptation task, in which participants used a joystick to direct an on-screen dot towards a destination until experimenters changed the orientation of how the joystick controlled the dot, tDCS to both motor cortex and the cerebellum improved accuracy in both older and younger adults to equal degrees. That is, older adult performance was always reduced compared to younger adults, but there was a main effect of stimulation (Panouillères, Joundi, Brittain, & Jenkinson, 2015). In another study of motor adaptation,

stimulation to motor cortex increased the ability to control grip force when picking up objects that had been unexpectedly made more or less slippery (Parikh & Cole, 2015).

Likewise, tDCS has been used to bolster skill acquisition in older adults. Wegscheider, Rumpf, Fricke, Weise, and Classen (2013) found that stimulation in older adults to either the primary motor cortex or the premotor cortex directly after motor sequence training resulted in greater learning for the sequence (relative to training alone) lasting for at least 22 hours after the training. Similarly, Zimerman and colleagues (2013) reported that stimulation applied to the primary motor cortex increased the amount of correct sequences performed in a skill-learning task. Other work shows that tDCS increases the effectiveness of training on tasks such as an implicit motor-learning task (Dumel et al., 2016), and a finger-tapping sequence task (Timmerman et al., 2015, experiment 2). Finally, participants trained on a motor task with their dominant hand benefit from stimulation to motor cortex corresponding to the opposite hand when transferring the task to the other hand (Goodwill, Daly, & Kidgell, 2015), and tDCS is known to augment the effects of visual feedback on this task (Hoff et al., 2015).

Working memory. A reliable finding among older adults is a decline in working memory capacity (Park et al., 2002), yet performance can be improved with tDCS. Applying tDCS to the left dlPFC increases performance on a verbal segment of the 2-back task, a task that requires constant updating of working memory (participants must listen to lists of stimuli and decide whether the currently listed stimulus is identical to one shown two presentations earlier) in older adults (Seo, Park, Seo, Kim, & Ko, 2011). Another study found that only highly educated older adults benefitted from tDCS applied to either the left or the right dlPFC on both verbal and visuospatial subtypes of the 2-back task (Berryhill & Jones, 2012). This suggests that some populations may be more or less susceptible to tDCS effects on cognition. A recent study has

combined tDCS with computer-assisted cognitive training for working memory capacity (WMC; see Glisky, Schacter, & Tulving, 1986) designed to give participants experience interacting with computers. In this study, bilateral stimulation, or stimulation to both left and right dlPFC, showed benefits in 2-back performance relative to a sham condition when tested immediately after study (showcasing online effects of stimulation) and both 7 and 28 days after the stimulation (showcasing *offline effects*; Park, Seo, Kim, & Ko, 2014). Similarly, it has been found that training-induced changes in WMC are apparent 1 month after training is over but only when paired with tDCS (Jones, Stephens, Alam, Bikson, & Berryhill, 2015). Interestingly, providing stimulation simultaneously with training on working-memory tasks leads to transfer to everyday tasks such as planning a driving route and organizing a calendar while distracted (Stephens & Berryhill, 2016).

Further work has employed tDCS on those diagnosed with Parkinson's disease. As this neurodegenerative disorder progresses, many cognitive functions, including working memory, rapidly decline (Lees & Smith, 1983). However, tDCS applied to left dlPFC has been found to increase accuracy on a 3-back task relative to sham stimulation (Boggio et al., 2006). This result exhibits the flexibility of tDCS effects, in that its effectiveness is not limited to healthy older adults, but instead is effective in many different populations.

Verbal fluency. Verbal fluency, or the ability to list as many words as possible based on a beginning letter (phonemic fluency) or certain categories (semantic fluency) is known to be impaired in older Parkinsonian patients (Azuma, Cruz, Bayles, Tomoeda, & Montgomery, 2003; Jankovic, 2008). However, tDCS applied to the left dlPFC increased the amount of words generated to verbal fluency prompts relative to sham stimulation and anodal tDCS applied to the temporal lobe in those with Parkinson's Disease (Pereiraet al., 2013). In a similar word-

generation task, Meinzer and colleagues (2013) found that simulation over the left inferior frontal gyrus (IFG) increased verbal fluency performance to the level of young adults and altered brain activity to show more "young-like" patterns when investigated with fMRI.

A general effect of cognitive decline in old age is the slowing down of mental functions (Salthouse, 1996), including slowing of language production (Burke & Shafto, 2004; Kemper & Sumner, 2001). However, tDCS can improve response times and accuracy in older adults in naming tasks. In the naming paradigm, participants are presented with pictures in quick succession and must name the subject of the pictures as quickly as possible (Bates et al., 2000). Performance of older adults suffers during this task possibly due to decline in word retrieval ability. However, the application of tDCS to either the left dlPFC (Fertonani et al., 2014) or the left inferior frontal cortex (Holland et al., 2011), both areas that are important for language production, during this task improves reaction time for older adults. The speeding of responses in older adults suggests that tDCS may be useful for rehabilitation of processing speed, an ability known to decline with age (Salthouse, 1996).

Episodic memory. Most relevant to the current work, tDCS (relative to sham stimulation) has been shown to improve (non-associative) memory in older adults. In these studies, episodic memory has typically been tested using two different methods: recognition and recall tests. Recognition tests require participants to identify whether stimuli are identical to those previously presented, whereas recall tasks require participants to reproduce studied stimuli. Prior work has shown that tDCS improves memory performance in older adults as measured by both procedures. In one study, tDCS to either left dlPFC or left temporal cortex increased ability to discriminate previously-seen from new images for individuals with Alzheimer's Disease (Boggio et al., 2009). tDCS applied to both temporal and parietal areas on either the left or right hemisphere

increases verbal recognition performance in participants that received a diagnosis for probable Alzheimer's Disease (Ferrucci et al., 2008), and in healthy older adults when applied to the left dlPFC or parietal cortex (Manenti, Brambilla, Petesi, Ferrari, & Cotelli, 2013). Word recall in older adults is increased with applications to left dlPFC relative to sham stimulation, and this benefit is apparent 2 days after the stimulation procedure (Sandrini et al., 2015), and perseveres 30 days after the stimulation procedure with multiple applications of stimulated sessions (Sandrini et al., 2014). tDCS was also found to improve proper name recall in healthy older adults when applied to left anterior temporal lobe (Ross, McCoy, Coslett, Olson, & Wolk, 2011). Taken together, these results indicate that both healthy and clinical older adults show memory benefits from tDCS application, whether memory is assessed with recognition or recall procedures. To provide a more complete picture of how tDCS affects memory performance as measured by both tests, I used both recognition and recall measures of face-name association memory in the current study.

It worth noting that these memory studies employed non-associative memory paradigms. To date, only one study has investigated associative memory performance in a sample of older adults. In this study, participants learned the relationships between items and their locations in an array (Flöel et al., 2012). When compared to sham stimulation, tDCS to a right temporoparietal area was found to improve recognition performance for the object-location associations when tested one week after the initial session, which displayed both the effectiveness of tDCS for improving associative recognition and the long-lasting, offline effects of tDCS on memory performance. However, this study uses a probabilistic learning paradigm in which participants saw many trials that highlighted either "correct" or "incorrect" pairings. Thus, it is not known

whether these effects will still be apparent under more traditional paired-associate learning materials procedures.

Testing generalizability, scaling, and enduring effects of tDCS. When testing tDCS effects on memory, researchers have made various theoretical assumptions that have yet to be empirically verified. First, little is known about the comparable effectiveness of tDCS protocols between younger and older adults. Research with older adults often does not include younger comparison groups with which to contrast the relative effects of stimulation with older adults (e.g., Berryhill & Jones, 2012; Flöel et al., 2012; Sandrini et al., 2014). Second, conventional thinking on tDCS protocols maintains that longer stimulation produces greater tDCS effects on cognition (e.g., Kalu, Sexton, Loo, & Ebmeier, 2012). That is, the longer the stimulation interval, the greater the change to cognition. If more stimulation means a greater effect on memory, it should be the case that multiple presentations under stimulation would produce greater effects on memory than singular presentations under stimulation. Finally, although much work has demonstrated that tDCS effects are apparent days after the original stimulated encoding session (e.g., Flöel et al., 2012), it is unclear whether this pattern will also be found for face-name association memory. In the next section, I will review work related to these ideas, and present how I tested these assumptions with the current work.

Memory effects of tDCS on younger adults. Memory studies with simultaneous use of younger and older adult populations is rare with tDCS. One such study found that tDCS to either dlPFC or parietal cortex was effective in improving word recall in both populations, but bilateral stimulation (anodal stimulation of either right or left hemispheres), was effective only for younger adults, while only left-hemisphere stimulation was effective in older adults (Meinzer et al., 2013). Effects of tDCS on proper name recall was tested in 2 different studies with different

populations, and although both populations showed improvement, the effective electrode positioning was reversed between age groups (Ross et al., 2010, 2011). Although work with both populations is in its infancy, it seems that tDCS is effective in both populations. However, it may be the case that effective parameters of tDCS differ for different populations.

Much more memory research with tDCS has focused on only younger adults. This work typically employs non-associative tests, but makes use of both recognition and recall tests. Younger adults show benefits from tDCS application (relative to sham) on recognition of visual shapes (Chi, Fregni, & Snyder, 2010), objects (i.e., cars and faces; Barbieri, Negrini, Nitsche, & Rivolta, 2016), foreign characters (i.e., Korean letters; Lu, Wang, Chen, & Xue, 2015), and words (Jacobson, Goren, Lavidor, & Levy, 2012; Javadi & Cheng, 2013, Javadi, Cheng, & Walsh, 2012; Javadi & Walsh, 2012; Manuel & Schnider, 2016; Pisoni et al., 2015). Recognition for associations can also be increased in younger adults, including for object-location pairs (England, Fyock, Gillis, & Hampstead, 2015), text-font color pairs (Gray, Brookshire, Casasanto, & Gallo, 2015), and importantly, forced-choice face-name pairs (Pisoni, Vernice, Iasevoli, Cattaneo, & Papagno, 2015). tDCS also results in increased recall of images (Penolazzi et al., 2010) and word pairs (Marshall, Mölle, Hallschmid, & Born, 2004) as well as long-term verbal recall (Jones et al., 2014). Finally, stimulation reduces false recall (e.g., producing an item not previously seen; Boggio, Jones, Gözenman, & Berryhill, 2009). Taken together, these results show that younger adults show similar memory benefits as older adults from tDCS. However, there has yet to be a direct comparison of tDCS effects on associative memory between older and younger populations, and therefore it is unknown whether tDCS effects on associative memory are comparable across age groups. Thus, I used younger adults in the current study, and tested if

the benefits of tDCS vs sham stimulation are comparable between older adults and younger adults. This reasoning leads to the first hypothesis of the current work:

Hypothesis 1: tDCS will lead to similar improvements in face-name association memory performance relative to sham stimulation in both older adults and younger adults.

Stimulation of multiple study trials. If more stimulation leads to bigger benefits to memory, repeated study under stimulation should increase the memory effects of tDCS for those trials. Because stimulation during one trial is expected to improve memory for the stimuli contained in that trial, it would seem likely that presenting trials twice during stimulation would enhance the effect of tDCS. Specifically, the amount of memory improvement for trials presented multiple times, compared to those shown once, should be larger under active stimulation compared to sham; that is, the effects of tDCS should be stronger under multiple study trials. Multiple study opportunities under stimulation has been typically conducted in one of two manners: during encoding, stimuli are either presented multiple times (i.e., Flöel et al., 2012; Jones et al., 2014), or participants are asked to repeat encoding until they are able to reach some memory criterion for the stimuli set (i.e., Marshall et al., 2004; Sandrini et al., 2014). This common practice may increase the magnitude of the stimulation effect, but this has not been subjected to an empirical test. In this study, half of the face-name pairs were presented twice during encoding, and half of the trials only once. This allowed systematic investigation of the interaction between tDCS effects and number of presentations during the stimulated encoding task. This leads to the second hypothesis in the current work:

Hypothesis 2: Memory improvement due to tDCS will be greater for trials that were presented twice during the encoding session than trials presented only once.

After effects of tDCS. Finally, since memory studies with tDCS have found behavioral effects lasting after the period of stimulation (i.e., Flöel et al., 2012; Parikh & Cole, 2014; Park et al., 2014), it is possible that measures conducted after a delay will also show benefits of the stimulation in the current study. These behavioral effects are ostensibly due to the long-lasting, offline effects of tDCS (Liebetanz et al., 2002; Nitsche et al., 2003, 2004). Thus, similar memory measures were conducted one day after the original stimulation session. This allowed a test of the offline effects of tDCS on face-name association memory. I made these measurements only one day after simulations to 1) decrease the likelihood of floor effects for this session, and 2) to minimize attrition for the study. This leads to the third and final hypothesis of the current work:

Hypothesis 3: tDCS will enhance face-name association memory performance relative to sham stimulation when memory is assessed one day after the initial stimulation session.

Method

Participants

I recruited 48 older adult (age 60-79; *M* = 65.63, *SD* = 4.90)) and 48 younger adult (age 18-35; *M* = 22.38, *SD* = 4.70) right-handed participants for this study. Participants were screened and excluded from participation for a personal or familial history of epilepsy, pacemakers, cochlear or metal implants, cuts, scrapes, or abrasions to the scalp, skull fractures, brain injury, brain surgery, and pregnancy, as all of these conditions may increase risk involved with tDCS exposure. Further exclusions were made for participants unable to speak English, who did not meet the handedness and age requirements, or who showed signs of dementia. Older adults were recruited from the Chicago surrounding community. Younger adults were undergraduate students at the University of Illinois at Chicago and from the surrounding community. All participants received $20 per hour for participation.

Materials

The faces in this study are from the FACES database (Ebner, Riediger & Lindenberger, 2010), a catalogue of high-quality, color photographs of people in front of grey backgrounds taken from the neck up. The age of the target faces ranged from 19-80. This specific sample of targets has equal number of younger (aged 18-30), middle aged (aged 39-55), and older adults (aged 69-80) and equal numbers of males and female targets. Pictures of faces were presented on a computer monitor, in front of a black background. Names for each face were taken from lists (from the Social Security Administration) of most common male and female names from the decades in which the targets would have been born. If a name was popular for both genders, the name was not used in the study.

Participants also completed tests of neuropsychological assessments to make sure that current younger and older adult samples were similar to those in past aging studies. These tests included measures of fluid intelligence (digit symbol and verbal fluency; Ekstrom, French, Harmon, & Derman, 1976; Hedden, Park, Nisbett, Jing, & Jiao, 2002; Wechsler, 1997) and crystallized intelligence (Shipley Vocabulary; Shipley, 1986). More specifically, the Digit Comparison and Digit Symbol tasks measured speed of processing, and participants decided whether a series number-string pairs were the same or different (Digit Comparison) or filled out empty boxes under symbols that all signaled a different digit for the participant to write (Digit Symbol). These measures were to be completed until a short amount of time had passed (45 seconds or one minute) and were scored according to completion rate by the time limit. The Digit Span task required the experimenter to read progressively longer series of numbers for the participant to recite from memory either forwards or backwards, and scoring was determined by the number of sequences correctly remembered. For the Verbal Fluency task, the experimenter gave each participant one minute to produce as many words as possible that either started with a provided letter or fit within a provided category. Scores indicated the number of words produced by the participant. Finally, participants chose among 4 possible words that best fit the definition of a target word for the Vocabulary tasks, and the scores indicated the number of correct answers. Scores on these measures fit the standard for older and younger adult samples. That is, younger adults usually outperform older adults on all measures except for vocabulary, in which older adults outperform younger adults. This was the case with the current data, except on two measures on which both samples performed similarly (See **Table 1**). Older participants then completed the Mini Mental State Exam (Folstein, Folstein & McHugh, 1975), which probed for probable dementia or Alzheimer's. All older adult participants scored within the normal range

for this measure, indicating that there were no abnormal cognitive impairments within the sample.

Finally, I also measured the mood of the participants in this study, to rule out distracting emotional states felt by participants upon entering the lab. Furthermore, stimulation near the targeted brain region may have effects on mood (Barrett, Della-Maggiore, Chouinard, & Paus, 2004) and it was important to rule this possibility out (See **Appendix A** for the mood questionnaire; See **Table 2** for means and standard deviations). On a 0 (strongly disagree) to 5 (strongly agree) scale, participants rated their agreement to statements related to anxiety, excitement, fatigue, confusion, sadness, frustration, dizziness, nausea, discomfort, and lack of focus when completing the mood questionnaire.

Procedure

The experimenter first prepared the participant to receive the stimulation (active or sham) and then provided training on the memory task. Participants completed the encoding session under stimulation. After this, participants completed the cued recall and recognition tests, respectively. After 24 hours, participants returned for follow-up memory tests (see **Figure 1** for a diagrammatic explanation of the procedure). Finally, participants completed the neuropsychological tests and provided detailed health and demographic information (See **Appendix B**).

Table 1

Means and Standard Deviations for Neuropsychological Measures Split by Age and Condition

Age	Condition	Digit Comp.		Digit Symbol		Digit Span		Verbal Fluency		Vocabulary	
Younger	Active	85.33	(14.82)	47.96	(6.93)	18.00	(3.79)	101.54	(24.42)	30.42	(5.09)
	Sham	78.63	(12.11)	45.13	(5.98)	17.50	(2.64)	93.04	(19.18)	29.21	(4.41)
Older	Active	67.50	(12.91)	35.79	(8.53)	19.04	(3.88)	96.29	(27.91)	34.00	(4.27)
	Sham	62.71	(9.80)	36.25	(6.65)	17.25	(3.96)	94.63	(22.60)	34.83	(3.67)

Table 2

Means and Standard Deviations for Mood Measures Taken Before and After Stimulation

Before Stimulation

Age	Condition	Nervous		Excited		Tired		Confused		Sad		Tense		Dizzy		Nauseous		Pain		Focus	
Younger	Active	.96	(1.04)	2.63	(1.13)	1.42	(1.18)	.13	(0.34)	.08	(0.28)	.29	(0.62)	.21	(0.66)	0.00	(0.00)	.08	(0.28)	.25	(0.44)
	Sham	1.29	(1.40)	1.88	(1.36)	2.13	(1.30)	.33	(0.82)	.42	(0.88)	.42	(0.78)	.25	(0.61)	0.00	(0.00)	.17	(0.48)	.50	(0.78)
Older	Active	1.04	(1.40)	1.43	(1.41)	.70	(0.93)	.26	(0.92)	.43	(1.16)	.39	(1.12)	.09	(0.42)	.09	(0.42)	.22	(0.67)	.13	(0.46)
	Sham	1.00	(1.04)	1.48	(1.24)	1.39	(1.56)	.22	(0.52)	.39	(0.78)	.65	(0.83)	.26	(0.69)	.17	(0.65)	.22	(0.67)	.35	(0.78)

After Stimulation

Age	Condition	Nervous		Excited		Tired		Confused		Sad		Tense		Dizzy		Nauseous		Pain		Focus	
Younger	Active	.33	(0.76)	1.75	(1.45)	1.29	(1.12)	.21	(0.51)	.08	(0.28)	.21	(0.51)	.33	(0.56)	0.00	(0.00)	.13	(0.34)	.29	(0.69)
	Sham	.33	(0.64)	.88	(1.15)	1.83	(1.17)	.33	(0.64)	.29	(0.69)	.25	(0.53)	.21	(0.59)	.08	(0.28)	.21	(0.51)	.83	(0.82)
Older	Active	.33	(0.56)	.92	(1.18)	.92	(0.97)	.33	(0.70)	.38	(0.92)	.33	(0.76)	.21	(0.51)	.13	(0.45)	.21	(0.51)	.50	(0.78)
	Sham	.08	(0.28)	1.04	(1.52)	1.50	(1.59)	.25	(0.53)	.42	(0.72)	.58	(1.10)	.25	(0.85)	.04	(0.20)	0.00	(0.00)	.46	(0.78)

tDCS stimulation. Participants received either anodal (1.5 mA) or sham stimulation (0.1 mA; double blinded) during the encoding session. The experimenter provided stimulation via an ActivaTek ActivaDose II Controller. Saline-soaked sponge electrodes were square-shaped, 25 cm^2. The anodal electrode was placed over an area analogous to the left dlPFC (i.e., F3) with the reference electrode (cathode) placement on the contralateral upper arm. Stimulation was turned on 4 minutes before the beginning of the encoding session to allow participants to habituate to physical sensations associated with the stimulation and lasted 25 minutes for both conditions. Participants rated their mood before and after the stimulation, and were also asked whether they received 1.5 mA, 0.1 mA, or if they were unable to tell the difference, as done before (Matzen, Trumbo, Leach, & Leshikar, 2015). After this question, participants were asked to guess the type of stimulation they received if they indicated that they could not tell the difference. This measure was termed the *blinding probe* (this was attached to the mood questionnaire; See **Appendix A**).

Encoding session. During the encoding session, participants viewed 60 face-name pairs, 30 presented once, and 30 presented twice, displayed with a name under a picture of a face for 5000 ms. These stimuli were presented in a pseudo-random order so that at least 4 trials separated the first from the second presentation of items shown twice. During that time, participants were asked to make a subjective judgment about whether the name "fit" the face (see **Figure 1a** for an example trial; see Sperling et al., 2003, for a similar procedure). Participants

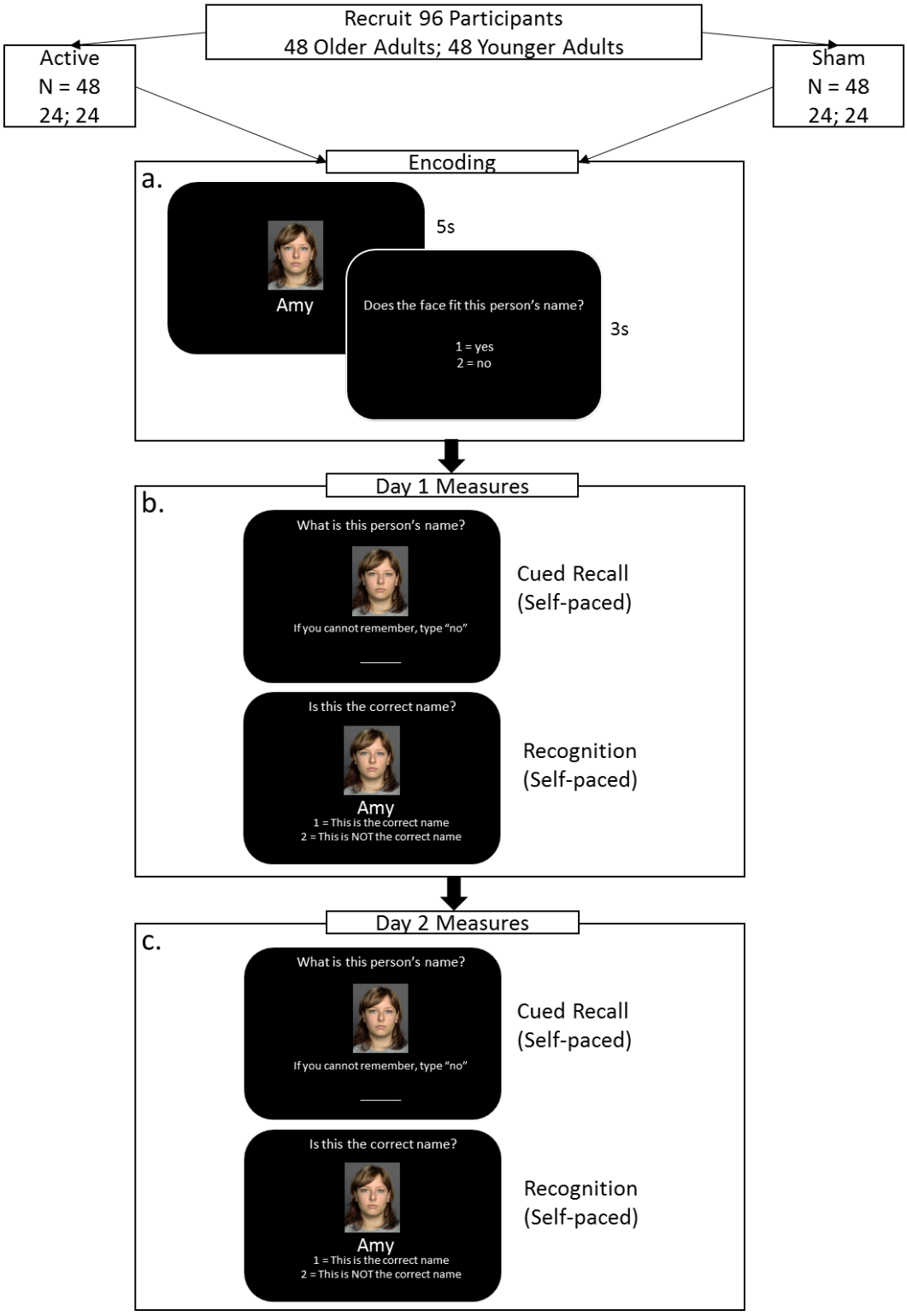

Figure 1. Example trials of encoding session and measures. a) Participants saw a face paired with a name, followed by a prompt of their fit judgment ("Does the name fit the face?"). b) Measures taken during Day 1 will include a cued recall task and a recognition task. c) Measures taken on Day 2 will be identical to Day 1 measures except for the pseudo-random order of trials and reversal of intact vs. rearraged presentation for each trial.

were instructed to press a key with their right index finger (1) to indicate a fit, or another key with their middle finger (2) to indicate a non-fit. This task was meant to ensure participants were attending to the association between the presented name and the presented face, and minimized the possibility that older adults used an inferior learning strategy, as has been demonstrated before with this sort of task (e.g., Naveh-Benjamin, Brav, & Levy, 2007). Trials were separated into five blocks lasting approximately 2-minutes each. After each block, participants filled out the comfort scale (See **Appendix C**) to assess any feelings associated with the stimulation (See **Table 3**). This phase of the experiment lasted approximately 15 minutes.

Cued recall test. After the encoding session, participants were shown the 60 faces presented during the encoding session in a pseudo-random order. Participants saw a single face and were told to type in the name that was presented with the face during the encoding session. Each letter appeared on the screen as participants typed them. This was a self-paced task, and participants were told to type "no" instead of guessing if they were not certain of a response. This helped ensure that participants were fairly certain of answers they provided.

Recognition test. After the recall session ended, participants completed the recognition test. During this phase, participants saw each of the 60 faces that were presented during the encoding session in a different pseudo-random order. This task followed a *paired-associate recognition* procedure, where each face was either presented with the correct (during study) name (intact pair), or a name that was paired with a different face during study (rearranged pairs). While viewing each face-name pair, participants decided whether the pair was intact or rearranged (see **Figure 1b** for example recall and recognition trials), and indicated their confidence in that decision on a 1 (Very Sure) to 3 (Uncertain) scale. The recognition task was also self-paced.

Table 3

Comfort Questionnaire Statistics at All Time Points

Time 0

Age	Condition	Itching	Burning	Tingling	Mental Fatigue
Younger	Active	3.54 (1.44)	2.42 (1.28)	3.04 (1.71)	1.13 (.34)
	Sham	1.46 (.66)	1.08 (.41)	1.63 (.71)	1.21 (.51)
Older	Active	2.42 (1.41)	2.17 (1.43)	2.08 (1.44)	1.04 (.21)
	Sham	1.21 (.51)	1.00 (.00)	1.04 (.20)	1.25 (.74)

Time 1

Age	Condition	Itching	Burning	Tingling	Mental Fatigue
Younger	Active	2.54 (1.18)	2.00 (1.02)	2.29 (1.49)	1.17 (.48)
	Sham	1.33 (.56)	1.08 (.28)	1.38 (.65)	1.21 (.51)
Older	Active	2.04 (1.08)	1.50 (.72)	1.50 (.83)	1.25 (.74)
	Sham	1.17 (.38)	1.00 (.00)	1.08 (.28)	1.21 (.51)

Time 2

Age	Condition	Itching	Burning	Tingling	Mental Fatigue
Younger	Active	2.21 (1.25)	1.63 (1.01)	2.04 (1.33)	1.33 (.56)
	Sham	1.29 (.46)	1.08 (.28)	1.21 (.41)	1.54 (.93)
Older	Active	1.83 (.87)	1.42 (.65)	1.54 (.72)	1.21 (.51)
	Sham	1.08 (.28)	1.04 (.20)	1.04 (.20)	1.25 (.53)

Time 3

Age	Condition	Itching	Burning	Tingling	Mental Fatigue
Younger	Active	1.92 (1.02)	1.50 (.78)	1.67 (.82)	1.63 (.92)
	Sham	1.29 (.46)	1.21 (.41)	1.33 (.48)	1.58 (.97)
Older	Active	1.83 (.96)	1.42 (.65)	1.46 (.72)	1.33 (.56)
	Sham	1.13 (.34)	1.08 (.28)	1.08 (.28)	1.29 (.55)

Time 4

Age	Condition	Itching	Burning	Tingling	Mental Fatigue
Younger	Active	1.88 (1.08)	1.38 (.82)	1.46 (.78)	1.71 (.95)
	Sham	1.33 (.48)	1.13 (.34)	1.25 (.44)	1.75 (1.11)
Older	Active	1.79 (1.02)	1.38 (.58)	1.54 (.72)	1.29 (.46)
	Sham	1.04 (.20)	1.04 (.20)	1.08 (.28)	1.29 (.62)

Follow-up memory tests. One day after the tDCS session, participants came back to the laboratory to complete the second-day (heretofore referred to as Day 2) memory tests. These tests were similar to the previously explained tests on the first day (Day 1 measures; See **Figure 1c**), but took place 24 hours later and the trials within each task were presented in a different pseudo-randomized order. For the second recognition task, trials were presented in the opposite form (intact vs. rearranged) that they were presented in for the first recognition task. That is, if a trial was presented in an intact form on Day 1, it was presented in rearranged form on Day 2 (and vice-versa). This was done to ensure the Day 2 test differed slightly from Day 1 tests.

Dependent Measures

Recall performance was calculated as a percentage of names each participant could recall out of the entire pool of names (misspellings were counted as correct). I also counted the number of times participants made no response and the number of times participants responded incorrectly (errors). Performance on the recognition task were quantified with a sensitivity measure, calculated with A' (Stanislaw & Todorov, 1999), that takes into account both hit rate (the ability to correctly respond "old" to "old" items) and false alarm rate (the rate at which participants respond "old" to "new" associations). Both hit rates and false alarm rates were also analyzed to better understand the effects of the stimulation on recognition. As I have shown previously (Leach, McCurdy, Trumbo, Matzen, & Leshikar, 2016), analyzing only composite measures of memory performance (such as A') may gloss over important details of tDCS effects on memory. Finally, recognition reaction times were also analyzed to test if tDCS sped up performance as has been shown before (Javadi, Cheng, & Walsh, 2012). For each of the analyses below, dependent measures included both recall and recognition performance measures. Each

analysis was conducted multiple times, once with each measure (recall, A', etc.), to provide converging evidence for each hypothesis.

Results

Results Overview

I will present the results of this experiment in the following order: First, I will explain the results of the analyses that tested the main hypotheses of the study (See **Memory Performance**). The percentage of names participants could recall and A' were the main variables of interest, but I also included percentage of recall misses (failures to provide an answer on a recall trial) and recall errors (incorrect answers given on recall trials) from the recall task and hit rate, false alarm rate, and reaction time measures from the recognition task to fully explore how the hypotheses are supported and unsupported by the data.

Second, because this study produced a rich data set, I present exploratory analyses on measures of confidence and memory biases, as well as differential effects of stimulation depending upon baseline cognitive acuity (See **Exploratory Follow-up Analyses**). Third, I report analyses of the questionnaire measures, including neuropsychological measures, comfort measures, blinding probe, and mood ratings (See **Questionnaire Measures**).

Memory Performance

To test Hypotheses 1, 2, and 3, I conducted 2 (Condition: active vs sham) x 2 (Age: younger vs older) x 2 (Presentations: 1 vs 2) x 2 (Session: day 1 vs day 2) Mixed ANOVAs with recall and recognition measures. The sections below report the results of this analysis broken down by each hypothesis. For each, I will review the expected results before detailing the actual results.

Hypothesis 1: Does tDCS facilitate memory? For Hypothesis 1, I expected to find a main effect of Condition such that participants in the active condition outperformed those in the

sham condition. I also did not rule out the possibility of a Condition x Age interaction, wherein the effects of tDCS would differ depending upon age group.

Recall measures. Recall results indicated a significant main effect of Condition, $F(1, 92) = 4.10$, $p < .05$, $\mu^2 = .04$, but this was qualified by a Condition x Age interaction, $F(1,92) = 6.30$, $p < .05$, $\mu^2 = .06$ (See **Table 4**). A follow-up analysis indicated that younger participants in the active condition outperformed those in the sham condition, $F(1,46) = 8.38$, $p < .05$, $\mu^2 = .15$, but there was no effect of the stimulation among older adults, $F(1,46) < 1$, *n.s.*.

To determine whether tDCS effects were driven by decreases in no responses and/or decreases in incorrect responses, both the percentage of trials participants did not provide an answer for (recall misses) and incorrect trials (recall errors) were analyzed. For recall misses, there was a significant main effect of stimulation, $F(1,92) = 5.71$, $p < .05$, $\mu^2 = .06$, whereby participants in the sham condition made more "no" responses than did those in the active condition. This was qualified, however, by a Condition x Age interaction, $F(1,92) = 6.50$, $p < .05$, $\mu^2 = .07$, such that this effect was only significant among younger adults, $F(1,46) = 12.73$, $p < .05$, $\mu^2 = .22$, but not among older adults, $F(1,46) < 1$, *n.s.*. For recall errors, however, neither the main effect of Condition nor the Condition x Age interaction were significant (both F's < 1). Taken together, these results indicate that tDCS was effective in increasing recall performance, but only in younger adults. Furthermore, the effect of tDCS on recall performance was driven by decreases to the number of misses instead of errors along with increased correct answers.

Table 4

Means and Standard Deviations for Recall Percentages Split by Trial Outcome, Number of Presentations, Day, Age, and Condition

Recall

		Day 1 Measures		Day 2 Measures	
Age	Condition	1 Presentation	2 Presentations	1 Presentation	2 Presentations
Younger	Active	0.17 (.11)	0.39 (.19)	0.23 (.12)	0.40 (.20)
	Sham	0.10 (.09)	0.27 (.12)	0.12 (.12)	0.27 (.13)
Older	Active	0.07 (.09)	0.19 (.15)	0.08 (.10)	0.16 (.14)
	Sham	0.09 (.08)	0.20 (.14)	0.09 (.07)	0.18 (.15)

Recall Misses

		Day 1 Measures		Day 2 Measures	
Age	Condition	1 Presentation	2 Presentations	1 Presentation	2 Presentations
Younger	Active	0.64 (.13)	0.38 (.17)	0.55 (.19)	0.39 (.18)
	Sham	0.73 (.13)	0.54 (.14)	0.72 (.18)	0.56 (.17)
Older	Active	0.68 (.13)	0.50 (.18)	0.65 (.18)	0.55 (.18)
	Sham	0.68 (.17)	0.52 (.18)	0.62 (.18)	0.54 (.19)

Recall Errors

		Day 1 Measures		Day 2 Measures	
Age	Condition	1 Presentation	2 Presentations	1 Presentation	2 Presentations
Younger	Active	0.19 (.10)	0.21 (.12)	0.20 (.11)	0.19 (.12)
	Sham	0.17 (.09)	0.17 (.11)	0.22 (.11)	0.18 (.12)
Older	Active	0.25 (.10)	0.28 (.17)	0.30 (.16)	0.28 (.17)
	Sham	0.24 (.14)	0.26 (.14)	0.29 (.17)	0.26 (.14)

***Recognition measures*[2].** For A', the effect of Condition was not significant, $F(1,91) < 1$, *n.s.*, but there was a significant Condition x Age interaction, $F(1,91) = 5.34$, $p < .05$, $\mu^2 = .06$. Follow-up analyses indicated a significant effect of Condition for younger adults, $F(1,45) = 4.31$, $p < .05$, $\mu^2 = .09$, but not for older adults, $F(1,46) < 1$, *n.s.*, which indicated that younger participants in the active condition outperformed those in the sham condition, but there was no effect for older adults (See **Table 5**). As prior work shows, tDCS can alter performance on A' by influencing the hit rate or the false alarm rate individually (Leach et al., 2016). It has also been shown that tDCS can have an effect on reaction times for recognition tasks, (Javadi, Cheng, & Walsh, 2012). However, main effects of Condition and Condition x Age interactions were not significant (all *p*'s < .14) for hit rates, false alarm rates, or reaction times, indicating that tDCS did not have a noticeable effect on these measures for either age group (See **Table 6** for reaction times). Taken together, the results show partial support for Hypothesis 1, in that tDCS was effective in increasing performance, but only for younger adults.

Hypothesis 2: Do effects scale with greater stimulation? For Hypothesis 2, I expected that more stimulation would lead to greater effects of the stimulation. That is, I predicted a Condition x Presentation interaction, such that the effects of tDCS are stronger for trials presented twice during a stimulated encoding session than trials presented only once. Unsurprisingly, there was a significant main effect for Presentation for both recall, $F(1,92) = 172.51$, $p < .05$, $\mu^2 = .65$, and A', $F(1,91) = 62.41$, $p < .05$, $\mu^2 = .41$, indicating that participants performed better on trials that had been presented twice during encoding rather than once. However, there was not a significant Condition x Presentation interaction for any outcome measure (all *p*'s > .11). Therefore, results did not support Hypothesis 2.

[2] Because of a computer malfunction, recognition performance for Day 2 was not recorded for one younger adult participant in the active stimulation condition. This individual was thus removed from recognition task analyses that included Day 2 measures.

Table 5

Means and Standard Deviations for Recognition Measures Split by Condition, Age of Participant and Session Day

Day 1 Measures

		1 Presentation						2 Presentations					
Age	Condition	Hit Rate		FA Rate		A'		Hit Rate		FA Rate		A'	
Younger	Active	.74	(.15)	.32	(.16)	.78	(.12)	.87	(.12)	.28	(.16)	.88	(.08)
	Sham	.73	(.14)	.39	(.15)	.74	(.14)	.86	(.11)	.31	(.15)	.86	(.08)
Older	Active	.74	(.16)	.59	(.23)	.62	(.20)	.86	(.10)	.54	(.21)	.74	(.13)
	Sham	.83	(.14)	.61	(.18)	.69	(.16)	.86	(.13)	.48	(.20)	.78	(.14)

Day 2 Measures

		1 Presentation						2 Presentations					
Age	Condition	Hit Rate		FA Rate		A'		Hit Rate		FA Rate		A'	
Younger	Active	.72	(.17)	.32	(.15)	.77	(.13)	.83	(.13)	.20	(.11)	.88	(.06)
	Sham	.70	(.16)	.38	(.15)	.73	(.13)	.76	(.14)	.32	(.18)	.79	(.13)
Older	Active	.76	(.17)	.55	(.21)	.68	(.15)	.78	(.16)	.56	(.26)	.69	(.15)
	Sham	.75	(.18)	.52	(.23)	.70	(.15)	.79	(.12)	.51	(.22)	.72	(.12)

Table 6

Means and Standard Deviations for Recognition Reaction Time Split by Trial Outcome, Day, Age, Condition, and Presentation

		Day 1 Measures									
		1 Presentation									
Age	Condition	Hits		False Alarms		Misses		Correct Rejections		All	
Younger	Active	2946.51	(734.57)	3608.98	(1261.85)	4065.80	(2003.97)	3386.93	(920.66)	3324.13	(777.45)
	Sham	3076.11	(766.56)	3393.91	(1008.85)	3816.00	(1475.09)	3366.91	(1046.00)	3271.92	(817.15)
Older	Active	3766.57	(1191.71)	3893.40	(1698.52)	5049.19	(2184.75)	4568.10	(1433.46)	4033.73	(1516.43)
	Sham	3502.29	(979.70)	4475.81	(1273.78)	5438.43	(4700.26)	4389.85	(1430.65)	3864.06	(1342.29)
		2 Presentations									
Age	Condition	Hits		False Alarms		Misses		Correct Rejections		All	
Younger	Active	2838.78	(1725.48)	3348.32	(1977.92)	2833.77	(2356.55)	3095.66	(880.87)	3074.39	(1261.35)
	Sham	2705.71	(749.85)	3473.64	(1525.88)	3655.10	(3011.56)	3505.63	(1179.87)	3163.36	(892.21)
Older	Active	3193.71	(868.10)	3763.17	(1191.03)	4015.98	(2055.37)	4544.25	(1629.46)	3628.15	(1182.83)
	Sham	3534.87	(1156.95)	4143.79	(1437.51)	4224.57	(2597.14)	5033.02	(2750.31)	3964.34	(1566.28)
		Day 2 Measures									
		1 Presentation									
Age	Condition	Hits		False Alarms		Misses		Correct Rejections		All	
Younger	Active	2786.18	(1328.92)	3009.35	(1584.00)	3262.51	(1733.53)	2620.01	(937.21)	2733.49	(1247.56)
	Sham	2980.55	(1140.04)	2881.35	(894.32)	3123.96	(1300.54)	2998.95	(892.24)	2913.80	(752.01)
Older	Active	3386.77	(1119.64)	4117.56	(1872.14)	4464.40	(1958.61)	5144.61	(5755.32)	3904.61	(2186.70)
	Sham	3356.06	(701.94)	3833.03	(1544.67)	4172.52	(2389.90)	4093.64	(976.19)	3720.24	(1156.27)
		2 Presentations									
Age	Condition	Hits		False Alarms		Misses		Correct Rejections		All	
Younger	Active	2285.33	(1029.10)	2480.79	(1503.57)	3689.69	(4090.26)	2539.58	(1024.63)	2613.76	(1553.74)
	Sham	2452.29	(560.83)	2815.27	(954.11)	2959.11	(1465.46)	2888.88	(853.25)	2745.60	(651.66)
Older	Active	3493.63	(1116.45)	3549.43	(1425.20)	4584.92	(2126.84)	4350.60	(2040.95)	3694.88	(1390.61)
	Sham	3290.35	(836.87)	3938.51	(1545.05)	5358.72	(3211.11)	4194.21	(952.65)	3692.61	(1105.96)

Hypothesis 3: Do effects persist after a 24-hour delay? For Hypothesis 3, I predicted to find offline effects of stimulation. That is, I hypothesized a significant difference between participants in the active versus the sham condition for measures taken on Day 2. I also did not rule out a Condition x Session interaction, such that the effect of the stimulation was stronger on Day 2, due to participants in the active condition experiencing a slower rate of decay. This interaction, however, was not significant for any measure (all *p*'s > .11), indicating that effects of tDCS were similar across sessions.

***Day 2 analyses*.** To test whether tDCS improvements were present on measures taken after a 24-hour delay, I conducted a planned 2 (Condition: active vs sham) x 2 (Age: younger vs older) ANOVA on *only* Day 2 measures. The analysis included the Age variable because Condition x Age interactions were present when collapsing across both days, making it seem likely that Age would be important to consider when analyzing Day 2 measures.

Recall measures. Participants in the active condition outperformed those in the sham condition with recall, $F(1,92) = 4.23$, $p < .05$, $\mu^2 = .04$, and this was qualified by a Condition x Age interaction, $F(1,92) = 6.35$, $p < .05$, $\mu^2 = .07$. Follow-up analyses showed that tDCS was effective in younger adults, $F(1,46) = 8.16$, $p < .05$, $\mu^2 = .15$, but not older adults, $F(1,46) < 1$, *n.s.*. Similarly, the main effect of Condition was significant for recall misses, $F(1,92) = 4.64$, $p < .05$, $\mu^2 = .05$, and this was qualified by a Condition x Age interaction, $F(1,92) = 7.82$, $p < .05$, $\mu^2 = .08$, indicating that tDCS reduced the amount of recall misses for younger adults, $F(1,46) = 12.17$, $p < .05$, $\mu^2 = .21$, but not older adults, $F(1,46) < 1$, *n.s.*. Neither the main effect of condition nor the Condition x Age interaction was significant for recall errors (both *F*'s < 1). Taken together, these results show that tDCS improved recall on Day 2 for only younger adults, and that this was done by reducing recall misses and not recall errors.

Recognition measures. The main effect of Condition was not significant for A' measures, $F(1,46) = 1.09$, $p = .30$, $\mu^2 = .01$, but there was a significant Condition x Age interaction, $F(1,91) = 3.97$, $p < .05$, $\mu^2 = .04$, such that tDCS significantly improved recognition performance for younger adults, $F(1,45) = 6.29$, $p < .05$, $\mu^2 = .12$, but not older adults, $F(1,45) < 1$, *n.s.*. Neither the main effect of Condition nor the Condition x Age interaction was significant for hits, false alarms, or reaction time (all *p*'s > .10).

ANCOVA. Finally, to test whether tDCS affected memory performance on Day 2 over and above its effect on Day 1 measures, each Day 2 measure was entered into a 2 (Condition: active vs sham) x 2 (Age: younger vs older) ANCOVA with Day 1 measures as a covariate. The Condition main effect was non-significant for A' and recall (both *p*'s > .13) as well as all other performance measures (all *p*'s > .32), indicating that although Day 2 performance was higher for the active than the sham condition, it is unlikely that tDCS had an effect on Day 2 measures over and above the Day 1 effects. Thus, Hypothesis 3 was partially supported by the data, as the beneficial effects of tDCS persisted after a 24-hour delay. However, this was likely a carryover effect from the performance benefit from the previous day.

Exploratory Follow-up Analyses

To more fully vet the current data for interesting trends to guide future research, I conducted several extra analyses. Confidence and bias measures were collected or calculated, respectively, during the recognition tasks, as well as memory performance depending upon target (the face shown during memory trials) age. Finally, I was able to look at tDCS effects depending upon the neuropsychological performance of individual participants. The analyses reported in this section provide a more nuanced understanding of the current data set as well as set up paths for new research.

Confidence and bias measures. During recognition tasks, participants indicated how confident they were in their decision on a 1 (Very Confident) to 3 (Uncertain) scale. Because participants chose from 2 different options (choosing whether a face-name pair was intact or rearranged), this yielded 6 different possible answers when combining the choice and confidence rating. Each of these responses was plotted for each participant on how likely they are to be correct when made. The resulting figure is known as a Response Operating Characteristic (ROC) curve, and the area under the curve (AUC) represents both accuracy and the likelihood that participants are more likely to be correct when they are more confident about their decision (Stanislaw & Todorov, 1999). AUC for both days was calculated for each participant and entered into a 2 (Condition: active vs sham) x 2 (Age: younger vs older) x 2 (Session: Day 1 vs Day 2) Mixed ANOVA to check for replication of the current results[3]. Although there was a significant main effect of Age, $F(1,91) = 31.85$, $p < .05$, $\mu^2 = .26$ (i.e., the younger adults outperformed the older adults), the Condition x Age interaction (whereby stimulation was effective only for younger adults) was marginal, $F(1,91) = 3.41$, $p = .07$, $\mu^2 = .04$. Thus, analyses with AUC only partially replicated the result that tDCS was effective in younger adults.

Second, a bias measure, B", was calculated for each participant. B" takes into account both hit rates and false alarm rates, and measures whether participants are biased towards either affirmative or negative responses during a recognition task (Stanislaw & Todorov, 1999). Scores range from -1 (extreme bias towards affirmative responses) to 1 (extreme bias towards negative responses). This measure was entered into a 2 (Condition: active vs sham) x 2 (Age: younger vs older) x 2 (Presentation: 1 vs 2) x 2 (Session: Day 1 vs Day 2) Mixed ANOVA to explore the effects of tDCS on bias. Unfortunately, neither the main effect of condition, $F(1,91) = 1.18$, $p = .28$, $\mu^2 = .01$, nor any interactions with condition (all p's > .17) were significant. However, the

[3] The participant for which Day 2 recognition measure was unavailable was left out of this analysis.

main effect of Age was significant, $F(1,91) = 5.48$, $p < .05$, $\mu^2 = .06$, replicating the commonly-found result that older adults ($M = -.25$, $SD = .03$) typically show more bias towards affirmative responses than younger adults ($M = -.14$, $SD = .03$).

Own-age bias. Because face targets varied in age, it is possible to examine memory effects contingent on the age of the targets. Younger and older adults use different cues to remember faces (Lin, Lendry, & Ebner, 2015) and for both populations this contributes to an own-age bias in face recognition (better memory for targets one's own age; Anastasi & Rhodes, 2005; Rhodes & Anastasi, 2012). Recall and A' performance was identified according to the age of the target face, and is shown in **Table 7**. To explore the effect of tDCS on own-age bias, I conducted a 2 (Condition: active vs sham) x 2 (Age: younger vs older) x 2 (Session: Day 1 vs Day 2) x 3 (Target Age: young vs middle vs old) Mixed ANOVA with both recall and A' measures. As expected, there was a significant Age x Target Age interaction for recall, $F(1,92) = 23.39$, $p = .28$, $\mu^2 = .20$, indicating a younger-adult bias for younger adults but an older-adult bias for older adults[4]. However, this bias was not influenced by the stimulation, as the Condition x Age x Target Age interaction was not significant, $F(1,92) < 1$, *n.s.*.

Neuropsychological splits. Finally, because tDCS may only benefit a subset of participants based on mental ability (Berryhill & Jones, 2012), it was important to explore whether only a subset of the younger adult sample benefitted from the stimulation based on their neuropsychological scores. A median split was performed on every neuropsychological score for each younger adult (based on the median for only the younger-adult sample). I performed a 2

[4] This bias was determined by follow-up paired-samples t-tests with Day 1 measures. For recall, younger adults remembered names of younger adult targets better than older adult targets, $t(47) = 4.54$, $p < .05$, d = .69, and middle adult targets, $t(47) = 2.89$, $p < .05$, d = .45, whereas older adults remembered names of older adult targets better than younger adult targets, $t(47) = 2.06$, $p < .05$, d = .32. Additionally, a similar Age x Target Age interaction was found for A', $F(1,91) = 5.24$, $p = .28$, $\mu 2 = .05$, but follow-ups did not identify any significant difference in memory for differently-aged targets (all t's < 1) except that younger adults were marginally better at remembering middle-adult targets than older-adult targets, $t(47) = 1.75$, $p = .09$, d = .24.

Table 7

Means and Standard Deviations of Recall and Recognition Performance Depending upon Age of the Target Face

Recall

		Day 1						Day 2					
Age	Condition	Young		Middle		Old		Young		Middle		Old	
Younger	Active	0.34	(.19)	0.26	(.14)	0.24	(.15)	0.36	(.20)	0.32	(.18)	0.25	(.14)
	Sham	0.21	(.12)	0.18	(.11)	0.15	(.13)	0.22	(.14)	0.19	(.13)	0.18	(.15)
Older	Active	0.13	(.12)	0.14	(.12)	0.13	(.11)	0.11	(.12)	0.13	(.13)	0.12	(.12)
	Sham	0.12	(.12)	0.14	(.11)	0.17	(.12)	0.13	(.13)	0.12	(.10)	0.15	(.12)

A'

		Day 1						Day 2					
Age	Condition	Young		Middle		Old		Young		Middle		Old	
Younger	Active	0.84	(.13)	0.85	(.09)	0.81	(.11)	0.85	(.11)	0.84	(.10)	0.79	(.10)
	Sham	0.79	(.16)	0.82	(.12)	0.80	(.12)	0.78	(.15)	0.77	(.17)	0.72	(.17)
Older	Active	0.70	(.14)	0.68	(.18)	0.67	(.22)	0.60	(.21)	0.72	(.17)	0.65	(.19)
	Sham	0.70	(.22)	0.72	(.16)	0.75	(.20)	0.66	(.24)	0.70	(.16)	0.71	(.17)

(Condition: active vs sham) x 2 (Split: high vs low) ANOVA for each neuropsychological measure using recall and A' as dependent measures. For each analysis, I looked for a Condition x Split interaction, such that tDCS was only effective on participants scoring high or low on each neuropsychological measure. For recall, this interaction was significant for Vocabulary scores, $F(1,44) = 5.52$, $p < .05$, $\mu^2 = .11$, and marginal for Digit Composition, $F(1,44) = 2.97$, $p = .09$, $\mu^2 = .06$, and Verbal Fluency, $F(1,44) = 2.78$, $p = .10$, $\mu^2 = .06$. Follow-ups on these interactions indicated that tDCS was effective at increasing face-name recall performance, but only for younger adults that scored high on the neuropsychological measures[5]. For A' analyses, there was only a marginal Condition x Split interaction for Vocabulary scores, $F(1,44) = 3.52$, $p = .07$, $\mu^2 = .07$, which was determined to indicate a similar pattern after follow-up analyses.

Questionnaire Measures

Neuropsychological tests. Older adults typically underperform compared to younger adults on these measures (except for Vocabulary, on which they outperform younger adults). This analysis was included to test whether our younger and older adult samples conformed to this general result. Additionally, I was interested in whether participants differed between stimulation conditions on these measures. To test these possibilities, neuropsychological measures were entered into a 2 (Condition: active vs sham) x 2 Age (younger vs older) ANOVA. There was a significant main effect of Condition for the Digit Comparison measure, $F(1,92) = 5.05$, $p < .05$, $\mu^2 = .05$, signifying that those in the active condition outperformed those in the sham condition. There was a significant main effect of Age for the Digit Comparison, $F(1,92) = 43.45$, $p < .05$, $\mu^2 = .32$, Digit Symbol, $F(1,92) = 52.92$, $p < .05$, $\mu^2 = .37$, and Vocabulary

[5] For example, for younger adults that scored high on the Vocabulary task, those in the active condition (n = 11; $M = .34$, $SD = .15$) outperformed those in the sham condition (n = 13; $M = .16$, $SD = .09$), $t(22) = 3.58$, $p < .05$, d = 1.5. However, there was no difference between the active condition (n = 13; $M = .23$, $SD = .11$) and the sham condition (n = 11; $M = .21$, $SD = .11$), $t(22) < 1$, *n.s.*. These relationships were similar for Digit Composition and Fluency splits.

measures $F(1,92) = 26.40$, $p < .05$, $\mu^2 = .22$, such that younger adults outperformed older adults on the Digit Comparison and Digit Symbol tasks, and older adults outperformed younger adults on the Vocabulary task. There were no Age x Condition interactions on any neuropsychological measure (all F's < 1.30).

Comfort ratings. As a test of the blinding procedures, ratings of physical sensations and mental fatigue were analyzed across stimulation conditions. I examined whether ratings increased or decreased over time and whether they differed according to age group. Each measure of physical sensation (Itching, Burning, and Tingling) was combined into one physical sensation measure ($\alpha = .83$; individual analyses of these measures are described in **Appendix D**). This sensation composite was entered into a 5 (Timepoint: time 0-4) x 2 (Condition: active vs sham) x 2 Age (younger vs older) mixed ANOVA (See **Table 3**). There were main effects of Timepoint, $F(1,92) = 49.01$, $p < .05$, $\mu^2 = .35$, Condition, $F(1,92) = 45.46$, $p < .05$, $\mu^2 = .33$, and Age, $F(1,92) = 6.73$, $p < .05$, $\mu^2 = .07$, whereby reported physical sensations dissipated over time[6], participants in the active condition felt more sensation than those in the sham condition, and younger participants felt more sensation than older participants. There were also significant Timepoint x Condition, $F(1,92) = 37.24$, $p < .05$, $\mu^2 = .29$ and Timepoint x Age, $F(1,92) = 9.42$, $p < .05$, $\mu^2 = .09$, interactions. Follow-up analyses indicated that the Timepoint x Condition interaction represented a stronger effect of Timepoint in the active condition $F(1,46) = 45.97$, $p < .05$, $\mu^2 = .50$, than in the sham condition, $F(1,46) = 3.04$, $p = .09$, $\mu^2 = .06$, and the Timepoint x Age interaction represented a stronger effect of Timepoint with younger adults, $F(1,46) = 45.266$, $p < .05$, $\mu^2 = .50$, than with older adults, $F(1,46) = 8.78$, $p < .05$, $\mu^2 = .16$. For both

[6] This was determined with follow-up paired-samples t-tests, in which reported levels of physical sensations at every timepoint was significantly greater than all the timepoints following it (i.e., time 0 was greater than times 1-4, time 1 was greater than times 2-4, etc; all p's < .05) except for the difference between time 2 and time 3, $t(95) = 1.28$, $p = .20$, $d = .14$.

interactions, a stronger effect of Timepoint indicated a larger decrease of sensation over time. Finally, these results were qualified by a significant Timepoint x Condition x Age interaction, $F(1,92) = 5.74$, $p < .05$, $\mu^2 = .06$, whereby the Timepoint x Condition interaction (that is, the effect of Timepoint was stronger in the active than the sham condition) was stronger with younger adults, $F(1,46) = 32.24$, $p < .05$, $\mu^2 = .41$, than older adults, $F(1,46) = 7.80$, $p < .05$, $\mu^2 = .15$. Together, these results indicate that participants felt more sensation earlier on, and sensations dissipated over time. Furthermore, samples that experienced more dissipation experienced greater sensations initially (i.e., younger adults and those in the active condition).

Additionally, I conducted independent-samples *t*-tests on sensations at each timepoint to determine when sensations in the active condition were higher than the sham condition. Results of these analyses showed that the difference between stimulation conditions was significant at every timepoint (all *p*'s < .05). Although sensations dissipated over time, the sensations reported by participants in the active condition never approached the level reported by those in the sham condition.

Measures of fatigue indicated a main effect of Timepoint, $F(1,92) = 21.19$, $p < .05$, $\mu^2 = .19$, which, unlike the other comfort measures, indicated that fatigue increased over time[7]. This was qualified by a Timepoint x Age interaction, $F(1,92) = 7.85$, $p < .05$, $\mu^2 = .08$, such that the effect of Timepoint (increased reporting of fatigue over time) was stronger for younger adults, $F(1,46) = 18.38$, $p < .05$, $\mu^2 = .29$, than older adults, $F(1,46) = 3.20$, $p = .08$, $\mu^2 = .07$.

Finally, as my previous work has shown correlations between comfort ratings and measures of memory performance (Leach et al., 2016), it was important to establish whether these measures are correlated in the current data set. Across all measures, only burning measured

[7] That is, reported sensations of mental fatigue increased between all timepoints and the timepoints preceding them (all *p*'s ¸.05) except for the difference between time 0 and time 1, $t(95) = 1.04$, $p = .30$, d = .08, and a marginal increase from time 3 to time 4, $t(95) = 1.95$, $p = .06$, d = .12.

at time 1 (correlated negatively with false alarms), $r(96) = -.24$, $p < .05$, and tingling measured at time 1 (correlated negatively with recall misses), $r(96) = -.21$, $p < .05$, correlated significantly with memory performance measures. This would indicate that participants who felt more burning made fewer false alarms, and that participants who felt more tingling made fewer recall misses. Because both burning and tingling were higher in the active condition, correlations between these measures were conducted for each condition separately. In the active condition, the negative correlation between time 1 burning and false alarms was still significant, $r(48) = -.32$, $p < .05$, but the negative correlation between time 1 tingling and recall misses became non-significant, $r(48) = -.19$, $p = .19$.

Blinding probe. Next, it was important to determine if participants could tell whether they were in the active or sham conditions based on their experiences in the laboratory. In the active condition, 10 participants (20.8% of active participants) correctly stated they were in the active condition, whereas 7 participants (14.6%) incorrectly stated they were in the sham condition. In the sham condition, 6 participants (12.5% of sham participants) stated their correct condition, whereas 7 participants (14.6%) incorrectly stated their condition. The 65 remaining participants (67.7 % of all participants) stated that they did not know which condition they were in. When prompting those participants to guess, 14 participants in the active condition (45.2 % of prompted active participants) correctly guessed their condition, whereas 17 participants (54.8%) guessed incorrectly. In the sham condition, 20 participants (64.5% of sham participants prompted) correctly guessed their condition, whereas 11 participants (22.9%) guessed incorrectly. From this data, I concluded that most participants were not able to tell which condition they were in based on their experiences in the laboratory, and that blinding was adequate, consistent with past research (Leach et al., 2016).

Mood ratings. Mood ratings were collected for 2 reasons. First, previous research has indicated that stimulation can alter affect in healthy participants (Barrett et al., 2004). Second, I wanted to make sure that participants in either stimulation condition, were not experiencing any significantly different mood states relative to the other condition during the experiment. To explore these possibilities and fully vet the mood questionnaire data, I entered each mood rating into a 2 (Timepoint: before vs. after) x 2 (Condition: active vs. sham) x 2 Age (younger vs older) mixed ANOVA (See **Table 2**[8]). Ratings of nervousness showed a main effect of Timepoint, $F(1,90) = 48.18$, $p < .05$, $\mu^2 = .35$, indicating that participants were more nervous before the stimulation than after. A similar main effect was found for excitement, $F(1,90) = 41.39$, $p < .05$, $\mu^2 = .31$, also indicating increased excitement before stimulation than after stimulation. For excitement there was also a main effect of Age, $F(1,90) = 6.05$, $p < .05$, $\mu^2 = .06$, whereby younger adults were more excited than older adults. For fatigue, there were significant main effects of Condition, $F(1,90) = 9.05$, $p < .05$, $\mu^2 = .09$, and Age, $F(1,90) = 5.92$, $p < .05$, $\mu^2 = .06$, such that participants in the active condition were less tired than those in the sham condition and that older participants were more tired than younger participants. Finally, there was a significant main effect of Condition for reported inability to focus, $F(1,90) = 4.04$, $p < .05$, $\mu^2 = .04$, as participants in the sham condition gave higher ratings for this than did participants in the active condition. To test if the differences in ratings of fatigue and inability to focus had an effect on memory performance, I ran correlational tests between all memory outcome measures for Day 1 (hit rate, false alarm rate, A', recall, recall misses, recall errors, and reaction times) and ratings of fatigue and inability to focus before the stimulation. None of the correlations were significant (all p's > .10).

[8] Due to experimenter error, two older adults, one from each condition, did not fill out mood measures and therefore are left out of this analysis.

Discussion

With this study, I tested the efficacy of tDCS to improve face-name associative memory in both younger and older adults. As the deficit for older adults is particularly high with face-name associative memory tasks compared to younger adults (Naveh-Benjamin et al., 2004), it is especially important to test ways to rehabilitate this type of memory. I further explored whether the effects of tDCS scale with more presentations during a stimulated encoding session and tested whether effects persist 1 day after the initial stimulation session. The findings indicate that these set of hypotheses were partially supported. Specifically, tDCS improved face-name associative memory for younger but not older adults, which partially supported Hypothesis 1. Hypothesis 2 of the study was unsupported, as more stimulation did not lead to larger tDCS effects. Effects were still apparent after a delay, which suggested an offline effect. However, the tDCS effect after the delay was similar to the effect before the delay. Therefore, it seems likely that the delayed effect was simply a carryover effect from the previous day.

Hypothesis 1

The results suggested that tDCS improves face-name associative memory performance for younger adults but not for older adults. Little research so far has highlighted the differential effects of tDCS based on age (although see Meinzer et al., 2013), and the results of this project show early evidence that the age of the population tested may be an important factor in stimulation effectiveness. Nevertheless, this work represents conceptual replication of prior work showing the ability of tDCS to improve memory performance outcomes in younger adults (e.g., Javadi & Cheng, 2012).

For older adults, however, tDCS did not increase the memory performance. There are three possible reasons for this. First was the use of associative-memory tasks in the current study.

Older adults show much greater deficits compared to younger adults on associative memory tasks than non-associative tasks (Old & Naveh-Benjamin, 2008a), and one of the main purposes behind the use of an associative task was to test the effectiveness of tDCS on a task in which older adults typically underperform. Although many research studies have found that tDCS can increase memory performance in older adults (e.g., Ferrucci et al., 2008), the majority of these studies have focused on non-associative memory. Older adults perform particularly poorly at associative memory, and past work has failed to improve associative memory when tested immediately after stimulation (i.e., Flöel et al., 2012). This result is inconsistent with tDCS findings, across both motor and cognitive domains, that the effects of tDCS are stronger in older adults compared to a younger control group (i.e., Fertonani et al., 2014; Hardwick & Celnick, 2014; Heise et al., 2014; Meinzer et al., 2013; Panouilleres et al., 2015; Ross et al., 2011; Zimerman et al., 2013, 2014). This could point to the particular difficulty older adults have with associative-memory tasks, which might not respond to brain-stimulation interventions.

Second, the specific manner in which current was applied in the current study may be suboptimal for memory improvements in older adults. Aging is associated with a functional reorganization of brain activity (e.g., Cabeza, 2002), and it is possible that the current application used in this study was not in the correct location for older adults (Although see Leach et al., 2016, for a different location that also failed to improve face-name memory in older adults). When comparing tDCS effects on episodic memory between older and younger adult samples, Meinzer and colleagues (2013) discovered that fewer of the stimulation sites led to improvement for older adults than for younger adults. Thus, different locations should be explored to locate target regions most applicable to improvements in associative memory for older adults.

Additionally, as all studies with tDCS have used a current between 1 and 2 mA (Prehn & Flöel, 2015), it is unknown what current amounts are most beneficial for older adults.

Finally, specific physiological differences between younger and older adults may have contributed to the differential effects of tDCS. Older adults suffer from loss of cortical thickness, particularly in prefrontal areas (West, 1996), which may impact the effect of stimulation to this region. Other age-related changes include alterations to skin thickness (Shuster, Black, & Mcvitie, 1975) and cortical spinal fluid volume increases (Resnick et al., 2000). These factors are untested, but may be important moderators of tDCS effects.

Turning to the result with younger adults, the current research replicates past work showing the benefits of tDCS to *recall* memory performance in younger adults (Jones et al., 2014; Marshall et al., 2004; Meinzer et al., 2013; Penolazzi et al., 2010; Pisoni et al., 2015; Ross et al., 2010). Furthermore, the current study extends the literature by adding face-name associative recall to the list of memory tasks that can show improvement from tDCS to the left dlPFC. It would seem that the use of tDCS results in robust improvements to recall performance. Because recall requires the active recollection of task stimuli (as opposed to recognition which may only require a feeling of familiarity with the cue provided at retrieval; Yonelinas, 2002), this would indicate that tDCS increased recollection in younger adults in the current work. This would be consistent with past research on tDCS and recollection (Gray et al., 2015).

Likewise, previous research has shown a wide range of tDCS effects on *recognition* memory in younger adults (Barbieri et al., 2016; Chi et al., 2010; Jacobson et al., 2012; Javadi & Cheng, 2013, Javadi et al., 2012; Javadi & Walsh, 2012; Lu et al., 2015; Manuel & Schnider, 2016; Pisoni et al., 2015), and the current work also finds that tDCS increases recognition memory. Furthermore, the current results replicate this work as well as past research on the

effects of tDCS on associative recognition in younger adults (England et al., 2015; Gray et al, 2015) Finally, this work extends past work on face-name associative recognition (i.e., Pisoni et al., 2015), by using a paired-associate recognition task instead of a forced-choice task and stimulating a different brain region (i.e., dlPFC). Together, along with the previous work, research has indicated that tDCS effects on recognition memory may generalize to many different types of stimuli to be remembered.

Finally, this study provides rare causal evidence of the importance of the left dlPFC to associative memory in younger adults. Although past evidence from brain-imaging studies have been correlational in nature (e.g., Murray & Ranganath, 2007), the current evidence shows that manipulating activity in or near the left dlPFC has a beneficial effect on memory performance in younger adults. This indicates the causal role this region plays in associative memory. Because the same result was not found in older adults, it could be the case that the causal relationship between dlPFC function and associative-memory performance erodes due to age. More research would be necessary to assert that conclusion, however.

Hypothesis 2

The prevailing view on tDCS effectiveness is that more stimulation should lead to greater cognitive effects (e.g., Teo, Hoy, Daskalakis, & Fitzgerald, 2011), but this has been untested in studies of memory. The current work presents evidence that more stimulation may not have an effect on tDCS improvements to memory performance. That is, there was no interaction between stimulation condition and the number of times a trial was presented, showing equality of tDCS effects. I had reasoned that when one trial is present during stimulation, the stimulation would lead to increased memory for that trial, and thus, multiple trials during encoding would increase the size of the tDCS effect. However, this was not supported by the data. This could either mean

that the effects of tDCS do not grow stronger as stimulation increases, the current manipulation of number of encoding trials is not the correct method to test this hypothesis, or that adding a single presentation was not a strong enough manipulation to test the scaling effects of stimulation.

Numerous manipulations may serve as an alternative to test this hypothesis. For instance, experimenters could provide longer stimulation, higher currents (e.g., Kalu, Sexton, Loo, & Ebmeier, 2012), or a greater number of multiple presentations that go beyond the manipulation used in this work. If all of these types of manipulation fail to show interaction effects, then it could be argued that the effects of tDCS on associative memory do not scale with further stimulation. If these manipulations produce different effects, it would show the scaling effects of tDCS are apparent only under specific testing situations, and may present other variables to interact with tDCS scaling.

Hypothesis 3

Additionally, this work adds to the growing number of studies showing that effects of tDCS last for a significant time after the original stimulation session (e.g., Sandrini et al., 2014). The memory benefit to younger adults in the active condition was apparent 24 hours after the initial stimulation session. This may display the offline effects of stimulation, and extends current knowledge of lasting effects of tDCS into the realm of face-name associative memory. However, other analyses performed to test this hypothesis calls into question the notion of an offline effect. That is, the lack of a Condition x Session interaction on any recall or recognition measures, as well as a lack of a Condition main effect with Day 1 performance used as a covariate, seems to bolster the position that enhanced memory on Day 2 was simply a carry-over

from enhanced performance on Day 1. That is, tDCS may have simply benefitted the encoding process, and retrieval was thus better on both testing days due to the stimulation.

Neuropsychological Measures

Interestingly, participants in the active condition outperformed those in the sham condition on tests of Digit Comparison. Because the Digit Comparison task took place after the stimulation and subsequent memory tests, it is possible that the increased Digit Comparison scores exhibit an unintended offline effect of the stimulation. That is, those in the active condition performed better due to the after-effects of stimulation on the task. Another possibility is that participants in the active condition were better at this task at baseline. However, because the other task that tested perceptual speed, Digit Symbol (strongly correlated with Digit Comparison, $r = .67$, $p < .05$), did not show any differences between conditions, this seems unlikely.

The testing of neuropsychological abilities is common in studies involving both younger and older adult samples. Typically, younger adults outperform older adults in all tests except for vocabulary, in which older adults perform better than younger adults. The current results replicate these relationships except for with Digit Span and Verbal Fluency. For these two measures, both samples performed similarly. However, because older adults showed the expected deficits in face-name associative-memory performance, it is unlikely that this dissimilarity with past research made a difference in the current study.

Limitations

One question that was not answered with the current study was whether tDCS effects on face-name memory gradually decline as participant age increases or drops off significantly when participants cross an age threshold. To answer this question, tDCS should also be tested with

middle-aged adults to create a sample that spans the entire adult lifecycle. Previous work has shown the importance of using a lifespan sample to enhance understanding of memory deficits (Bender et al., 2010).

Another limitation of the current study is that participants in the sham condition were more tired and less focused during the experiment, including before the stimulation. This is a limitation of the current study, and stresses the importance of replication in a sample that does not show the same baseline differences. However, because these measures taken before the stimulation did not show any relationship to memory performance, it seems likely that baseline mood difference between conditions did not alter the results of the study.

Exploratory Results

The richness of the current data set allowed analysis of variables that are usually not explored in tDCS research, such as feelings of confidence and memory bias. Preliminary results based on these variables seem to indicate that they are unaffected by stimulation, although future research might test this possibility further. Nevertheless, the result that only younger adults that scored above the median on the Vocabulary test is potentially important (pending replication) and replicates previous research that has tested whether subsets of participants high in mental ability are particularly benefitted by stimulation (e.g., Berryhill & Jones, 2012). This result adds to the growing literature linking tDCS effects to baseline mental acuity or baseline performance (e.g., Leach et al., 2016; Learmonth, Thut, Benwell, & Harvey, 2015).

Conclusion

In the current study, I found that tDCS improves face-name associative memory for younger, but not older adults, and this improvement persisted after a 24-hour delay. I also found that the effects of tDCS do not scale with the number of presentations during a stimulated

encoding task. These data replicate and extend previous research. Furthermore, the data gathered for the current study can be used to answer a host of questions regarding the use of tDCS in current research. This study contains numerous tests that can be used to elucidate many unknowns in the current state of the field.

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Appendix A: Mood Questionnaire

MOOD QUESTIONNAIRE
Entrance/Exit

ID#_____ Date of Visit_____

Please answer the following questions by circling the appropriate number, where:
0 = not at all, strongly disagree
1 = very mildly, disagree
2 = mildly, slightly disagree
3 = mildly, slightly agree
4 = significantly, agree
5 = very much so, completely, strongly agree

1)	I feel nervous:	0	1	2	3	4	5
2)	I feel excited:	0	1	2	3	4	5
3)	I feel tired or fatigued:	0	1	2	3	4	5
4)	I feel confused or disoriented:	0	1	2	3	4	5
5)	I feel sad or down:	0	1	2	3	4	5
6)	I feel tense or frustrated:	0	1	2	3	4	5
7)	I feel dizzy or light-headed:	0	1	2	3	4	5
8)	I feel nauseous:	0	1	2	3	4	5
9)	Physically, I feel pain or discomfort:	0	1	2	3	4	5
10)	I feel unable to concentrate or pay attention:	0	1	2	3	4	5

If this is being completed after the tDCS session, please answer the following:

Do you know whether you were receiving:

(A) 2.0 mA (B) 0.1 mA (C) I could not tell the difference

If you marked (C), if you were forced to choose either 2.0 mA or 0.1 mA as the condition you believe you received, which condition would you pick?

Why do you feel that you received the condition you selected?

Appendix B: Health and Demographics Questionnaire

Participant # _____
Experimenter: _____
Date: _____

Demographics Questionnaire

Please do not write your name on this form. It will be stored separately from any other information that you complete during this study and will not be linked with your responses in any way. The information will allow us to provide an accurate description of the sample.

For the following items, please select the *one* response that is most descriptive of you or fill in the blank as appropriate.

1. Gender: female ☐ male ☐ **2**. Current Age (in years): _____

3. Ethnicity (check all that apply):
☐ Asian or Pacific Islander ☐ Asian Indian
☐ Black/African American (non-Hispanic) ☐ Caucasian/White
☐ Native American ☐ Latino/Hispanic ☐ Puerto Rican
☐ More than one race (specify): _____
☐ Other: _____

4. Education *completed* (check the highest level)
☐ Less than high school graduate (highest grade completed? _____)
☐ High school graduate/G.E.D
☐ Some college, or trade, technical or business school (how many years? _____)
☐ Bachelor's degree
☐ Some graduate work (how many years? _____)
☐ Master's degree
☐ M.D., J.D., Ph.D., other advanced degree

5. Is English your native and primary language?
☐ Yes
☐ No (please specify your native/primary language _____)

6. Compared to other people your own age, how would you rate your physical health?

☐	☐	☐	☐	☐
Much Worse Than Average	Worse Than Average	Average	Better Than Average	Much Better Than Average

7. How satisfied are you with your present health?

☐	☐	☐	☐	☐
Not At All Satisfied	Not Very Satisfied	Neither Satisfied Nor Dissatisfied	Somewhat Satisfied	Extremely Satisfied

8. How often do health problems stand in the way of doing the things you want to do?

☐	☐	☐	☐	☐
Never	Seldom	Sometimes	Often	Always

Appendix C: Comfort Questionnaire

Time Point_____ Time_____

tDCS Comfort Rating

Circle the number which best describes how much **skin itching** you are feeling. 1 is a very mild amount and 10 is an extremely high amount that is incredibly uncomfortable. If you report a 7 or higher, the experiment will automatically discontinue:

1 2 3 4 5 6 7 8 9 10

Circle the number which best describes how much **skin burning** you are feeling. 1 is a very mild amount and 10 is an extremely high amount that is incredibly uncomfortable. If you report a 7 or higher, the experiment will automatically discontinue:

1 2 3 4 5 6 7 8 9 10

Circle the number which best describes how much **skin tingling** you are feeling. 1 is a very mild amount and 10 is an extremely high amount that is incredibly uncomfortable. If you report a 7 or higher, the experiment will automatically discontinue:

1 2 3 4 5 6 7 8 9 10

Circle the number which best describes how much **mental fatigue** you are feeling. 1 is a very mild amount and 10 is an extremely high amount that is incredibly uncomfortable. If you report a 7 or higher, the experiment will automatically discontinue:

1 2 3 4 5 6 7 8 9 10

Appendix D: Analyses of Individual Sensation Measures

I entered each participant rating of comfort into a 5 (Timepoint: time 0-4) x 2 (Condition: active vs sham) x 2 Age (younger vs older) mixed ANOVA (See **Table 3**). For participant ratings of itching during the experiment, there were main effects of Timepoint, $F(1,92) = 36.64$, $p < .05$, $\mu^2 = .29$, Condition, $F(1,92) = 41.06$, $p < .05$, $\mu^2 = .31$, and Age, $F(1,92) = 4.64$, $p < .05$, $\mu^2 = .05$, whereby itching dissipated over time[9], participants in the active condition felt more itching than those in the sham condition, and younger participants felt more itching than older participants. There were also significant Timepoint x Condition, $F(1,92) = 22.34$, $p < .05$, $\mu^2 = .20$ and Timepoint x Age, $F(1,92) = 5.78$, $p < .05$, $\mu^2 = .06$, interactions. Follow-up analyses indicated that the Timepoint x Condition interaction represented a stronger effect of Timepoint in the active condition $F(1,46) = 33.54$, $p < .05$, $\mu^2 = .42$, than in the sham condition, $F(1,46) = 3.29$, $p = .08$, $\mu^2 = .07$, and the Timepoint x Age interaction represented a stronger effect of Timepoint with younger adults, $F(1,46) = 38.66$, $p < .05$, $\mu^2 = .46$, than with older adults, $F(1,46) = 6.19$, $p < .05$, $\mu^2 = .12$. For both interactions, a stronger effect of Timepoint indicated a larger decrease of itching over time. Finally, these results were qualified by a significant Timepoint x Condition x Age interaction, $F(1,92) = 6.61$, $p < .05$, $\mu^2 = .07$, whereby the Timepoint x Condition interaction (that is, the effect of Timepoint was stronger in the active than the sham condition) was stronger with younger adults, $F(1,46) = 28.77$, $p < .05$, $\mu^2 = .39$, than older adults, $F(1,46) = 2.16$, $p = .15$, $\mu^2 = .05$. Together, these results indicate that participants felt more itching earlier on stimulation, and sensations dissipated over time. Samples that experienced

[9] This was determined with follow-up paired-samples t-tests, in which reported levels of itching at every timepoint was significantly greater than all the timepoints following it (i.e., time 0 was greater than times 1-4, time 1 was greater than times 2-4, etc; all *p*'s < .05) except for the difference between time 2 and time 3, $t(95) = 1.62$, $p = .11$, and between 3 and time 4 measures, $t(95) < 1$, *n.s.*.

more dissipation were samples that experienced greater sensations to start (i.e., younger adults and those in the active condition).

Analysis of burning measures indicated main effects of Timepoint, $F(1,92) = 22.87$, $p < .05$, $\mu^2 = .20$, and Condition, $F(1,92) = 28.31$, $p < .05$, $\mu^2 = .24$, whereby burning dissipated over time[10] and participants in the active condition felt more burning that those in the sham condition. These main effects were qualified by a Timepoint x Condition interaction, $F(1,92) = 32.57$, $p < .05$, $\mu^2 = .26$, such that the effect of Timepoint (decrease of burning over time) was stronger in the active condition, $F(1,46) = 29.75$, $p < .05$, $\mu^2 = .40$, than the sham condition, $F(1,46) = 2.84$, $p = .10$, $\mu^2 = .06$.

For measures of tingling, there were significant main effects of Timepoint, $F(1,92) = 32.56$, $p < .05$, $\mu^2 = .26$, Condition, $F(1,92) = 20.21$, $p < .05$, $\mu^2 = .18$, and Age, $F(1,92) = 7.03$, $p < .05$, $\mu^2 = .07$. Similar to itching measures, these main effects indicated that tingling dissipated over time[11], feelings of tingling were higher in the active condition than the sham condition, and younger participants reported stronger feelings than older participants. These main effects were qualified by Timepoint x Condition, $F(1,92) = 18.23$, $p < .05$, $\mu^2 = .17$, and Timepoint x Age, $F(1,92) = 12.91$, $p < .05$, $\mu^2 = .12$, interactions. Timepoint effects were stronger in the active condition, $F(1,46) = 27.31$, $p < .05$, $\mu^2 = .37$, than sham condition, $F(1,46) = 5.80$, $p < .05$, $\mu^2 = .11$, and stronger among younger participants, $F(1,46) = 34.11$, $p < .05$, $\mu^2 = .43$, than older participants, $F(1,46) = 3.05$, $p = .09$, $\mu^2 = .06$, respectively.

Because there was a significant effect of Condition on each of these comfort measures (itching, burning, and tingling), it is important to test at which timepoint (if any) participants in

[10] For burning, reported sensations were greater at time 0 than at any other timepoint (all p's < .05) and sensations reported at time 1 and time 3 were greater than those reported at time 4, $t(95) = 3.04$, $p < .05$, and $t(95) = 2.15$, $p < .05$, respectively.

[11] For tingling, reported sensations at times 0 and 1 were greater than those reported all other timepoints (all p's < .05).

both conditions are reporting similar levels of sensation. For itching, participants in the active condition reported greater sensations than participants in the sham condition at all timepoints, and the same relationship held between conditions for burning and tingling at timepoints 0, 1 and 2 (all p's < .05). Thus, differences between conditions lasted throughout the entire stimulation period for itching, and for most of the stimulation period for burning and tingling.

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Curriculum Vitae

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EDUCATION

University of Illinois at Chicago, 2009-present
Division: Social Psychology
Degree: Master of Arts and Doctor of Philosophy (expected Fall 2016)

Murray State University, 2005-2008
Major: Psychology
Minor: Spanish
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TEACHING EXPERIENCE

2014-2015
Instructor
University of Illinois at Chicago
Statistics in the Behavioral Sciences (Spring 2014)
Introduction to Psychology (Summer 2014, Fall 2014, Fall 2015)
Social Psychology (Summer 2015)

2009-Present
Teaching Assistant
University of Illinois at Chicago
Introduction to Psychology (Fall 2009)
Personality Psychology (Spring 2010, Fall 2010, Spring 2016)
Social Psychology (Fall 2010, Spring 2015)
Laboratory in Social Psychology (Spring 2011, Fall 2011, Spring 2012, Fall 2012, Spring 2013, Fall 2013, Spring 2014)
Statistics in the Behavioral Sciences (Summer 2013, Fall 2013)

PUBLICATIONS

1. McCurdy, M.P., **Leach, R.C.,** & Leshikar, E.D. (2017). The generation effect revisited: Enhancements for item and context memory. *Journal of Memory and Language*, 92, 202-216.
2. **Leach, R., C.,** McCurdy, M., P., Trumbo, M., C., Matzen, L., E., & Leshikar, E., D. (2016). Transcranial stimulation over left inferior frontal gyrus increases false alarms in an associative memory task in older adults. *Healthy Aging Research, 5,* 1-6.
3. Matzen, L. E., Trumbo, M. C., **Leach, R. C.,** & Leshikar, E. D. (2015). Effects of non-invasive brain stimulation on associative memory. *Brain research*, *1624*, 286-296.

4. Wiedmann, M., **Leach, R.**, Rummel, N. & Wiley, J. (2012). Does group composition affect learning by invention? *Instructional Science, 40 (4),* 711-730.
5. Wiedmann, M., **Leach, R.,** Rummel, N., & Wiley, J. (2015). Mathematical skills and learning by invention in small groups. In Y. H. Cho, I. S. Caleon, & M. Kapur (Eds.), *Education Innovation Series. Authentic problem solving and learning in the 21st century* (pp. 249–265). Springer Singapore.

PRESENTATIONS

1. **Leach, R.** (2008, April). *Social norming vs. personal alcohol use*. Poster presented at the annual meeting of the Scholar's Week conference, Murray, KY.
2. **Leach, R.** (2008, April). *Changes in alcohol perceptions based on current usage*. Colloquium talk given at the annual meeting of the Scholar's Week conference, Murray, KY.
3. **Leach, R.,** & Waddill, P. J. (2008, May). *Personal drinking behavior and the believability of alcohol norm information.* Poster presented at the annual meeting of the Association for Psychological Science, Chicago, IL.
4. Waddill, P. J., Mitchell, C., & **Leach, R.** (2010, November). *Predicting object location memory from simple and complex working memory spans.* Poster presented at the 51st Annual Meeting of the Psychonomic Society, St. Louis, MO.
5. **Leach, R.,** Larson., J., R., & Wiley, J. (2011, May). *I believe you're right: The effect of confidence on group performance outcomes.* Paper presented at the annual meeting of the Midwestern Psychological Association, Chicago, IL.
6. **Leach, R.,** Wiley, J., & Larson., J., R. (2012, May). *Who's the boss? Groups perform better when experts are dominant.* Poster presented at the annual meeting of the Association for Psychological Science, Chicago, IL.
7. **Leach, R.,** Wiley, J., & Larson., J., R. (2012, July). *What Did You Say? Repetition during Discussion and Group Decision Making*. Poster presented at the annual meeting of INGroup, Chicago, IL.
8. Pandya, R., **Leach, R.,** McCurdy, M., Leshikar, E.D. (April 2015). *Adaptive memory: Test of the future simulation hypothesis.* Poster presented at the UIC Student Research Forum, Chicago, IL. (NOTE: First place, Social Sciences Division)
9. McCurdy, M.P., **Leach, R.,** & Leshikar, E.D. (November, 2015). *Unconstrained generation improves the generation effect: Benefits for item and context memory.* Annual Meeting of the Psychonomics Society, Chicago, IL.
10. Perez, J., **Leach, R.,** McCurdy, M., Motyl, M., Leshikar, E.D. (April 2016). In Search of a person memory mechanism underlying ideological migration. Poster presented at the UIC Student Research Forum. Chicago, IL.
11. **Leach, R.,** McCurdy, M. P., & Leshikar, E., D. (2016, May). *Transcranial stimulation of dorsolateral prefrontal cortex improves face-name associative memory.* Poster to be presented at the annual meeting of the Association for Psychological Science, Chicago, IL.
12. McCurdy, M.P., **Leach, R.,** & Leshikar, E.D. (2016, May) *The generation effect revisited: Enhancements for item and context memory*. Poster presented at the International Meeting of the Psychonomics Society, Granada, Spain / Annual meeting of the Midwestern Psychological Association, Chicago, IL.

13. McCurdy, M.P., **Leach, R.,** & Leshikar, E.D. (May, 2016). *Enhancing the generation effect: Unconstrained generation improves item and context memory.* Annual meeting of the Association for Psychological Science, Chicago, IL.
14. McCurdy, M.P., **Leach, R.,** & Leshikar, E.D. (May, 2016). Unconstrained Generation Improves the Generation Effect: Benefits for Item and Context Memory. Poster presented at the International Psychonomics Society Annual Meeting, Granada, Spain.

UNDERGRADUATE MENTORING

- Rachele FioRito (Fall 2010-Spring 2011) The Effect of Confidence on Group Performance Outcomes
- Helina Washkowiak (Spring 2011) The Effect of Confidence on Group Performance Outcomes
- Kareyma Hope (Spring 2012) The Effect of Confidence on Group Performance Outcomes
- Zoie Meyers (Spring 2014) Context Memory Benefit As a Result of Survival Processing
- Rhiday Pandya (Spring 2014) Adaptive Memory: A Test of the Future Simulation Hypothesis
- Haajra Narmawala (Spring 2014) Data coding, analysis.
- Diala Abughish (Fall, 2015-Spring, 2016) Session running, Data Analysis

ACTIVITIES AND MEMBERSHIPS

- Member of the Midwestern Psychological Association (2010-present)
- Member of the Association for Psychological Science (2010-present)

AWARDS

- Harry S. Upshaw Award for Excellence in Teaching (Spring 2015)
- Provost Award for Graduate Research ($1500)