Direct Current Stimulation of Right Anterior Superior Temporal Gyrus During Solution of Compound Remote Associates Problems

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ABSTRACT

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During Solution of Compound Remote Associates Problems

J. Jason van Steenburgh, M.A.

Background: Research has implicated the right temporal lobe in verbal insight problems. Gamma frequency activity is coincident with insight, and fMRI showed there was greater hemodynamic activity when first seeing problems eventually solved with insight. fMRI research localized the activity to the rASTG. Direct current stimulation (DCS) can be used to modulate neuronal activity and has both enhanced and disrupted cognition via temporal lobe targets.

Objectives: To determine if rASTG activity drives insight processes or is epiphenomenal.

Main Hypotheses: Depolarizing anodal stimulation would enhance insight solutions; while hyperpolarizing cathodal stimulation would impede insight solutions.

Methods: 28 normal participants solved CRA) problems during 3 sessions while receiving 3 types of DCS. Participants were asked if they solved each problem with insight or analytic processes. Rate, speed, accuracy, and proportion of insight solution were compared to see if rASTG stimulation affected insight processes.

Results: Anodal stimulation was associated with fewer analytic solutions, decreased time to insight solution and decreased insight error rate. Cathodal stimulation increased time to insight solution and increased insight error rate.

Conclusions: Direct current stimulation alters solution strategies for compound remote associates problems, perhaps via effects on left-hemisphere-mediated impasse or coarse semantic integration at rASTG.

BACKGROUND AND SIGNIFICANCE

A greater understanding of the process by which humans achieve insight during problem solving could help with the development of optimal solution strategies for addressing both mundane problems and more complex problems. Understanding insight may also provide a path to achieving clinical endpoints, such as enhancing problem solving and improving recall.

After detailing a working definition of insight and summarizing what has been learned about insight from previous behavioral research, the following section describes how this research project was designed to overcome some of the confounds that have plagued previous investigations. It also describes some recent uses of transcranial direct current stimulation (tDCS or DCS) to study problem solving. The section ends with a description of how this investigation used tDCS to alter the methods by which participants solved problems as well as the speed and accuracy with which they solved them.

1.1 Insight

Before it is possible to review the mechanisms of insight, it is first necessary to define insight and to decide what interpretation of the research conducted to date best characterizes how insight fits within the greater framework of problem solving strategies.

1.1.1 Essential elements of insight

First, most researchers agree that insight involves a sudden conscious realization of the solution to a problem. Insight is characterized by a feeling that the solution is obviously correct—an often surprising or emotional experience known as the ‘Aha’ moment (Kounios et al., 2006).

The second element of insight requires that the problem solver restructure or change his or her thinking about some aspect of the problem. Gestalt psychologists have consistently identified the importance of restructuring in insight processing (see Ohlsson, 1984 for a review). Essentially, they believed that restructuring in problem solving occurs as you attempt (and fail) to solve the problem—you simply look at it a different way. According to the cognitive view (Kaplan & Simon, 1990; Ohlsson, 1992), problem solvers develop a representation of the problem and apply heuristics to transform the problem space so that it looks like the solution space. Eventually, when progress stops, they apply the “restructure when stuck” heuristic (Kaplan & Simon, 1990). According to Schilling (2005), who has developed a network model of cognitive insight, insight solutions require solvers to make an atypical association. The atypical association yields a “shortcut” in an individual’s network of representations—the shortcut rapidly decreases the path length between multiple representations of problem space and reorients an individual’s understanding of the relevant relationships. This reorientation (restructuring) subsequently prompts a cascade of other connections. There is also great debate (Dominowski & Dallob, 1995; Smith, 1995; Weisberg, 2006) about what drives restructuring of the problem space and to what degree impasse is necessary for restructuring. Although this research did not investigate aspects of impasse per se, the definition of insight presented here includes a stipulation that some degree of impasse is necessary to prompt the solver to restructure the problem. Regardless of why restructuring occurs, investigators of almost every theoretical orientation agree that reinterpreting the problem is a requirement for insight, and it is a critical element of the theory of verbal insight (Jung-Beeman et al., 2004) that provides the framework for the research presented here.

The third defining quality of insight is the use of all-or-none parallel processing, which seems to render most aspects of the insight strategy inaccessible to meta-cognition. First, solvers usually cannot report the processes that allow them to overcome the impasse and restructure the problem so that it is amenable to solution (Bowden, Jung-Beeman, Fleck, & Kounios, 2005; Maier 1931). Second, solvers using insight also cannot report the intermediate stages of the solution process itself (Metcalfe & Wiebe, 1987; Ben-Zur, 1989; Smith & Kounios, 1996), even after restructuring has occurred. Their experience is unlike that of solvers using analytic (non-insight) or search solutions, which tend to use a step-by-step or serial processing approach and are amenable to meta-cognition.

In summary, insight solutions seem suddenly and obviously correct and are accompanied by an affective dimension that is commonly described as the ‘aha’ experience. The solution is reached only after the solver is forced to restructure or reinterpret the problem, and solution processes are unavailable to meta-cognitive analysis. Now that insight has been characterized for the purposes of the investigation described here, it will be instructive to review some of the research that identified the qualities of insight just discussed.

1.1.2 Different kinds of insight

Many of the problems used to investigate insight can be sorted into one of three categories: 1) object-use problems, in which the problem solver must realize that one of the objects available to him or her can be used in a different way to solve the problem; 2) spatial insight problems, in which solvers must see beyond the assumed spatial limits of the solution, and 3) verbal insight problems, in which solutions rely on reinterpretation of verbal components of the problem. Research involving each type of insight problem has revealed elements common to insight solutions in general. What has been learned from the three types of problems will be briefly discussed below.

1.1.2.1 Object-use problems: Many of the pioneering studies of insight processes began with Gestalt psychology and that influence remains prominent. One of the first Gestalt psychologists to study insight was Wolfgang Köhler, who reported sudden movements in chimpanzees as they apparently realized that they could use a stick as a rake to more effectively reach their food (1925). In a series of experiments, Norman Maier observed complex problem solving. The most famous example was the Two Strings problem, in which he asked students to tie two strings together that were hung from the ceiling too far apart for participants to reach. The solution is to tie one of the provided objects to one string and swing it like a pendulum toward the other and then catch it while holding the other string (Maier, 1930; 1931). Duncker (1945) observed students as they attempted to solve a problem that required them to secure a lit candle to a wall with tacks. He concluded that students had to overcome *functional fixedness:* they had to realize that the box that contained the tacks could be used to solve the problem if one used the tacks to fasten the box to the wall where it could serve as a shelf on which the candle could be set. These are all examples of "object use" insight problems, and the main finding in the studies involving humans was that when hints were provided as to alternate uses of objects, participants were more likely to gain insight. Most of the early research was observational and involved only sparse data collection. Later research has shown that object-use tasks are mostly perceptual/mental tasks. When researchers manipulated variables related to the objects themselves, there was very little effect on solution rates (Jacobs & Dominowski, 1981); it was the restructuring of one's concept of what an object can be used for that was vital to achieving insight.

1.1.2.2 Spatial insight problems: Another type of insight problem requires spatial insight. The most familiar example is the 9-dots problem in which people are presented with nine dots in a 3x3 square array and told to connect them with four contiguous straight lines. Solvers must break their fixation suggested by the arrangement of the dots into a square and "think outside the box" (figure 1, Appendix A) to realize that they can extend a line out beyond the three dots (Scheerer, 1963).

In another classic insight problem, solvers are asked to plant four trees that are equally spaced from one another. Solvers often report insight when they solve the problem by planting the trees in a triangle with a deep hole or tall mound in the center for the fourth tree—planted thusly, the trees are in the shape of a pyramid and are equidistant. Like object-use problems and insight problems in general, spatial insight problems require solvers to reach an impasse and then break from default assumptions (such as the assumption that the solution must remain within the boundaries suggested by the problem elements), and restructure around an expanded or changed concept of what the solution can entail.

1.1.2.3 Verbal insight problems: Another type of problem requires verbal insight. These problems can be separated into two types according to what kind of failures they tend to produce: *wrong answer* and *no answer*. Problems of the first type tend to mislead solvers into producing the wrong answer. An example of a wrong answer problem is the problem of the lilies. *Water lilies double in area each day. On the first day of summer, there is one lily on the lake. Sixty days later, the entire lake is covered. On which day is the lake half covered?* Solvers often reason that the lake would be covered in half of sixty days, but the answer is gained from the first statement. If the lake is all covered, it was half covered the day before (on the 59th day). When told they are incorrect, solvers must discard the idea of a linear relationship between lily population and time and attend to other potentially relevant information contained in the first sentence. When solvers fail to solve the second type of verbal insight problem, they usually time-out and produce *no answer*. Two examples of this type include anagrams and compound remote associates problems. When solving anagrams, solvers must unscramble a group of letters to produce a word (melip→

impel; suroc→ scour, etc.). To solve compound remote associates problems, one is given three words and must find a solution word that forms a compound word or phrase with the target words (French, car, shoe → horn). In describing their experiences with anagrams and compound remote associates problems, participants often describe an 'Aha' experience in which solutions suddenly 'pop' into conscious awareness (Bowden & Jung-Beeman, 2003a, Novick & Sherman, 2003). Solvers often show little evidence of incremental problem solving (Smith & Kounios, 1996). In the same experiments, participants also describe serial hypothesis-testing approaches in which they approach problems systematically, attempting a series of solution candidates until they succeed. Use of verbal insight problems has shown that the same problems can be solved with both insight and noninsight strategies.

Although much has been done to describe the qualities of insight, and consensus is building around some of the core defining characteristics described here, there is considerable disagreement among insight researchers about the mechanisms of insight.

1.1.3 Special Process vs. Business as Usual

When attempting to incorporate insight within problem solving theories, insight researchers have vigorously debated whether insight processes recruit unique resources that are different from those employed in analytic solutions, or if insight is no different than normal problem solving. Theorists holding the later view have been described as belonging to the 'Business-as-usual' camp (Seifert et al., 1995). They argue that the processes by which problems are solved via insight are the same as those used in analytic or search solutions, but that it is only the affective experience that is different (Weisberg & Alba, 1981; Weisberg 1986; Perkins, 2000; Atchley, Keeney & Burgess, 1999; Weisberg, 2006).

Many researchers identify the strong emotional qualities of the insight experience and the inexplicability of the process as evidence that the cognitive mechanisms involved in achieving insight solutions must be distinct from ordinary approaches. Those adhering to the view that a distinct mechanism drives insight solutions hold the ‘Special-Process’ view and evidence to support their view is steadily mounting (Smith & Kounios, 1996; Schooler & Melcher, 1995; Bowden & Jung-Beeman, 2003; Luo, Niki & Phillips, 2004; Mai, Wu, & Luo, 2004; Sergent & Dehaene, 2004; Jung-Beeman et al., 2004; Kounios et al., 2006; Kounios et al., 2008; Aziz-Zadeh, Kaplan & Iacoboni, 2009). Much of the recent research arguing for a special-process view of insight relies on neuroimaging data that has demonstrated differences in electrophysiology and neural activation between events in which problems were solved by insight and those solved with analytic solutions. The research agenda proposed here will be based on the assumption that insight is a special process that is distinct from analytic problem solving.

The debate among researchers in the two camps has probably continued for so long because, until recently, insight has been difficult to study. Much of that difficulty can be traced to problems with stimuli and the measurement of insight, which will be described in the next section.

1.1.4 Challenges of studying insight in the laboratory

For more than 80 years, researchers have been using problems to try to systematically evoke insight so that it can be studied in the laboratory. Such investigations have often been conducted backwards. Researchers started with a problem that seemed to elicit insight solutions, studied participants as they wrestled with the problem, and then drew conclusions about insight. Although much has been learned about insight in this way, it has been difficult to isolate insight processes from analytic processes due to varied methods of detecting insight and problematic characteristics of the stimuli used to elicit insight. The following section will describe some of the hurdles to insight research in more detail and describe how the use of compound remote associates problems addressed some of these problems in the investigation reported here. (For more detail on this argument and the use of CRA problems in research, see Bowden, Jung-Beeman, Fleck, & Kounios, 2005).

1.1.4.1 A priori assumption of insight: Much of the previous research investigating insight has involved careful study of participants in the act of solving a problem or small group of problems whose answers have been categorized *a priori* as requiring insight. One of the most obvious reasons this approach has been problematic is that researchers have assumed that certain problems yield insight without verifying the experience (Auble, Franks, & Soraci, 1979; Wills, Soraci, Chechile, & Taylor, 2000). Although problem solvers may frequently report experiences of insight when solving an “insight” problem, even regular occurrences of insight do not preclude the possibility of analytic or search solution strategies (Weisberg, 2006). In such studies, investigators may have actually been studying processes that involved a mix of insight and analytic solutions. The assumption that problems are always solved with insight has often caused researchers to overlook the possibility of directly comparing insight and noninsight solutions of the same types of problems.

1.1.4.2 Measuring the occurrence of insight: Although some subjective elements of insight, such as the emotional experience, are difficult to study outside of self-report, the all-or-none processing that characterizes insight has been studied in several different ways and aspects of that processing have been exploited to show whether or not insight has occurred.

Unfortunately, the act of assessing whether all-or-none processing has occurred often confounds studies that attempt to compare insight and noninsight processes.

In several of the pioneering studies of insight, researchers asked participants to “talk aloud” to describe their thought processes while solving presumed “insight” problems (Duncker, 1945; Durkin, 1937), and participants were consistently unable to describe how they achieved insight. Metcalfe and Wiebe (1987) asked participants to rate their feelings of warmth (warmer feelings indicating that solvers were closer to a solution) or whether they thought they “knew” the answer (in spite of not having reached a solution) at several points during the solution process for both insight and noninsight problems. Participants’ feelings of knowing predicted solution of algebra and noninsight problems, but not insight problems. Feelings of warmth predicted accuracy over the course of solution in noninsight rather than insight problems.

Although these meta-cognitive approaches helped reveal the inaccessibility of partial solution information during insight solutions, they are not useful ways to objectively differentiate insight from noninsight processes in order to study insight. They confound studies attempting to describe other differences between insight and noninsight processes because meta-cognitive processes may interfere with insight strategy solution accuracy but do not affect analytic strategies, a finding called “verbal overshadowing” (Schooler, Ohlsson & Brooks, 1993). Such processes may also distort the degree to which problem solvers resort to insight solution strategies because such strategies crucially depend on a momentary shift of focus away from an ineffective problem representation, or on unconscious processing (Bowers, Regehr, Balthazard, & Parker, 1990; Schooler, Ohlsson & Brooks, 1993) that is disrupted by language (Koestler, 1964; Schooler & Melcher, 1995).

Because the few known ways of discriminating insight from noninsight processes disproportionately interfere with insight processes, researchers continue to rely on self-report (Jung-Beeman et al., 2004; Kounios et al., 2006; MacGregor & Cunningham, 2008; Aziz-Zadeh, Kaplan and Iacoboni, 2009; Anderson et al., 2009). Although self-report is vulnerable to demand characteristics and participant interpretations of the definition of insight, there is a long history of effective use of self-report in studying memory (Gardiner & Richardson-Klavehn, 2000) and other aspects of cognition, and it can be an effective method of studying insight (Bowden, Jung-Beeman, Fleck & Kounios, 2005). There is evidence that self-reporting of problem solving experiences can be valid, as long as the reports do not require participants to provide in-depth analysis of cognitive strategies (Ericsson & Simon, 1993). The validity of self-reports has been generally validated by brain imaging research as well (Baars, 2003; Kirchhoff and Buckner, 2006; Lutz, Lachaux, Martinerie and Varela, 2002).

1.1.4.3 Problem heterogeneity and small problem sets: Many of the traditional insight problems; such as the 9-dots problem (Scheerer, 1963; Newell & Simon, 1972), the tree-planting problem, and the candle problem (Duncker, 1945; Lung & Dominowski, 1985; Weisberg & Alba, 1981), are quite difficult and take a long time to solve (Weisberg, 2006). Once solved, their solutions often become ‘bound’ to the problem (Dominowski & Dallob, 1995; Knoblich et al., 1999; Ormerod, MacGregor, & Chronicle, 2002), and thus they are difficult to use in repeated-measures designs. Although insight solutions of these problems may share some common elements, the wide variety of cognitive mechanisms required to solve them (Bowden, Jung-Beeman, Fleck & Kounios, 2005) makes it difficult to control confounding sources of variation when independent variables are introduced. The problems’ time consumption and difficulty limits the number that can be given to only a few, which narrows stimulus sampling and threatens external validity.

1.1.4.4 Why large sets of small problems are ideal for insight research: To help address some of the issues outlined above, Edward Bowden and Mark Jung-Beeman (2003a) developed a set of 144 compound remote associates (CRA) problems. These problems are modeled after problems on the remote associates test (Mednick, 1962) and have been normed on a sizeable group of university students. A CRA problem begins with the simultaneous presentation of three words. Solvers are asked to generate a solution word that forms a compound word or two-word phrase with each of the target words. For example, for the group pine/crab/sauce the solution would be apple, which yields pineapple, crab apple, and applesauce. According to Bowden and Jung-Beeman (2003a), these problems have three properties that demonstrate they can elicit insight: solvers often report the “aha!” feeling; the problems misdirect (or fail to direct) retrieval processes; and solvers’ processing is inaccessible to meta-cognition. CRA problems are also useful for generalizing about insight because many of the same resources that are used to solve them are used to solve more difficult classic or traditional insight problems (Ansburg, 2000; Dallob & Dominowski, 1993; Schooler & Melcher, 1995).

CRA problems have several characteristics that make them more useful to researchers than traditional insight problems.

1) They have been normed for use with young adults, including solution frequencies and means and standard deviations of solution times for each problem.
2) They can be solved quickly, so a single session can include a large problem set.
3) They have unambiguous single-word answers, which eliminates the need to interpret or score solutions and responses are easily documented.

4) They are easily presented in a small space (such as a computer screen) and in rapid order. This allows for less confounded dependent variables, especially with regard to response times. Researchers can also more easily manipulate independent variables, such as presentation time and location (Bowden & Jung-Beeman, 2003a).
5) Most importantly, CRA problems can be solved with both insight and noninsight processes. Because each problem can be solved relatively quickly, participants can report their solution strategies without having to interrupt the problem solving process. This addresses issues about the *a priori* assumption of insight and allows for a direct measure of insight.

All of these qualities make CRA problems ideal candidates for use as stimuli in behavioral research. The same qualities are especially advantageous for neuroimaging research, which often requires participants to remain still and ideally compares large groups of events that are similar in all ways except for the independent variable of interest (insight, noninsight).

Although CRA problems have many qualities that make them suitable for use as stimuli in studies of insight, other sets of problem stimuli have been developed for many of the same reasons. Tasks reported in the literature that can be repeated many times include: riddles (Mai, Luo, Wu, and Luo, 2004; Luo and Niki, 2003), using cues to understand initially incomprehensible sentences (Luo, Niki, and Phillips, 2004), anagrams (Novick and Sherman, 2003), matchstick addition (Knoblich, Ohlsson, Haider and Rhenius, 1999; Chi & Snyder, 2011), and rebus puzzles (MacGregor and Cunningham, 2008). Collectively these problems have been referred to as 'Mini-insight' problems. They all can be solved relatively quickly and there are large numbers available.

1.1.4.5 Advantages of CRA problems: This investigation sought to add to extant literature on mechanisms of insight. Because most of the investigations on insight mechanisms have targeted verbal insight (discussed below), a discussion of which mini-insight problems are most appropriate for investigating the neural mechanisms of insight will be confined to stimuli designed to elicit verbal insight: CRA problems, incomprehensible sentences, and anagrams. Riddles are not exclusively verbal insight problems. Many rely on spatial or object-use insights rather than semantic relationships, so they also will not be considered.

The problem with using incomprehensible sentences as stimuli is that they tend to produce a large number of wrong answers. 'Wrong answer' verbal problems are less useful than 'no answer' verbal problems when researching insight because the solver does not perceive a lack of progress to a solution (they have produced an answer and may not know it is wrong); therefore the solver does not reach impasse and is not driven to restructure. As previously discussed, restructuring is a critical quality for insight within the framework of this research. There is also evidence that in solving CRA problems, those who tend to use more noninsight strategies make more errors of commission, perhaps reporting an incremental solution, while those reporting a general tendency to engage in insight strategies make more errors of omission (Kounios et al., 2008). Hence wrong-answer verbal insight problems seem less likely than no-answer verbal insight problems to produce insight as we have defined it.

Anagrams have a similar set of advantages compared to CRA problems; however, when solving anagrams people develop expertise with practice (Kounios et al., 2008; Novick & Sherman, 2003). This can confound repeated-measures designs.

In summary, research exploring the characteristics of insight has provided a definition of insight as an emotional 'aha' experience of solution realization that is prompted by restructuring after impasse and characterized by all-or-none processing. Much of the research attempting to characterize insight has been confounded by backwards designs based on sometimes faulty assumptions about problems, difficulties with measuring the occurrence of insight, and variability due to problem heterogeneity and small problem sets. However, recent innovations in the development of stimuli that can produce both insight and noninsight solutions have allowed researchers to begin to move forward with studying the mechanisms of insight. The next section will review findings about the neural mechanisms of insight.

1.2 Neural Correlates of Insight Processing

The experiment described here examined the neural correlates of verbal insight because the vast majority of research into insight mechanisms has used verbal problems. This section will begin by summarizing key findings of research investigating the neural correlates of semantic processes that are thought to be involved in verbal insight, followed by behavioral studies of verbal insight implicating the right hemisphere. Finally, a review of pertinent neuroimaging studies of verbal insight will be followed by an explanation of the neural mechanistic theory of verbal insight on which this research was based.

1.2.1 The right hemisphere's role in semantic processes

Converging evidence from several studies of semantic priming supports the notion that while the left hemisphere engages in strong and targeted "fine" semantic coding, the right hemisphere engages in more coarse semantic coding (for a review, see Bowden & Jung-Beeman, 1998, Chiarello, 1998, or Jung-Beeman, 2005). According to the right hemisphere coarse semantic coding theory (based primarily on lexical priming studies), when people are presented with individual words to comprehend, the right hemisphere is diffusely activated: secondary word meanings are engaged (Burgess & Simpson, 1988), as is information distantly related to the word being considered (Beeman et al., 1994; Chiarello & Richards, 1992).

Bowden & Jung-Beeman (2003b) speculated that when right hemisphere language areas are damaged, the coarse semantic coding for which those areas are responsible is interfered with, which may explain why patients with right hemisphere lesions struggle to draw inferences (Brownell, Potter, Bihrle & Gardner, 1986), a finding that is likely relevant for more complicated verbal insight problems.

Kircher, Brammer, Andreu, Williams, and McGuire (2001) used fMRI to study neural activity when participants were asked to generate words to complete low frequency sentence stems. Compared to when participants were asked to read completed stems, or to select which word would fit the stem better, those asked to generate words had more activity in the right lateral temporal cortex. The authors speculated that the right lateral temporal cortex is also related to the processing of linguistic context, and is specifically related to the integration of a sensible final word into the context of the sentence.

Seger and colleagues (2000) used fMRI to record neural activation when they asked participants to generate usual and unusual noun-verb associations. When asked to generate typical associations, there was the expected increase in left inferior frontal cortical activity. However, when they asked people to generate unusual associations, there was additional activity in large areas of the right frontal lobe, left middle frontal gyrus and bilateral cerebellum. They concluded that it was the demand that verbs be unusual, rather than the difficulty of the task itself that caused the additional right frontal activation. The tendency of right frontal cortex to activate in response to the need to produce unusual semantic associations is in accord with neuroimaging research that has implicated right temporal areas in insight processes (discussed below).

Abdullaev and Posner (1998) also studied unusual semantic relationships. Using EEG, they found that ERPs were unilateral to the left hemisphere when participants were asked to generate closely related verbs to match with stimulus nouns, but when participants were asked to generate unusual relationships, ERPs were bilateral, which suggests that the ‘unusual’ stipulation alone activated right hemisphere areas.

1.2.2 The role of the right hemisphere in insight problems

Mark Jung-Beeman and Edward Bowden (2000) investigated the time course of hemispheric differences in solution activation for CRA problems. They theorized that because solving insight problems requires more unusual associations, after solvers begin to work on problems they would be more likely to have solution-related activation in the right hemisphere than in the left hemisphere. They hypothesized that such asymmetry results from the left-hemisphere’s tendency to mediate fine semantic coding while the right hemisphere mediates the coarse semantic coding required to restructure the problem. They tested their theory by allowing participants to work on CRA problems for 7 s and then tested solution-related priming by asking participants to name words presented to either the left visual field (right hemisphere) or the right visual field (left hemisphere). Participants named solution words faster when presented to the left visual field (right hemisphere) than when presented to the right visual field (left hemisphere) for both solved (+43 ms) and unsolved (+24 ms) problems. They also found that when participants were asked to decide whether the target word was the solution (yes or no) for an unsolved problem, they made decisions significantly faster when target words were presented to the right hemisphere and were not sacrificing accuracy for speed.

These results generally replicated findings from a previous study by the same authors (Bowden & Beeman, 1998) in which problems were presented for 15 s. In a follow-up experiment with the same variables but a 2-s problem presentation, the right hemisphere advantages were no longer significant, although they were marginally significant for men (+24 msec, $p<.06$). They concluded that about 3 s after problem presentation, semantic activation in the left hemisphere begins to focus—which is usually advantageous, except when an unusual meaning is intended—thus, the focus is at the expense of solution-related information. Because right hemispheric semantic activation continues to be diffuse, solution-related activation persists. This is consistent with the idea that unconscious right hemispheric processing contributes to insight solutions.

Bowden and Beeman noted that their findings were in accord with the findings of previous researchers (Fiore & Schooler, 1998) who showed that hints to insight problems are more effective when presented to the left visual field (right hemisphere) than when presented to the right visual field (left hemisphere).

1.2.3 Functional neuroimaging studies of verbal insight

In the past 5 years, researchers have begun to use neuroimaging techniques to investigate insight solution strategies while people solve verbal problems. The majority of the studies show correlations between verbal insight and activity in the anterior cingulate cortex (ACC), right dorsolateral prefrontal cortex (rDLPFC), and right superior temporal cortex.

In an fMRI investigation of insight, Luo, Niki and Phillips (2004) had 13 subjects read incomprehensible sentences followed by solution cues that would eventually trigger an alternative interpretation of a concept that was critical to understanding the sentence, e.g., *'You could not tell who it was, because a professional took the photo of that old man (x-rays).'* Or, *'His position went up because his partner's position went down (See-saw).'* Participants were presented with a sentence for seven seconds and asked if they understood it. Then they were shown the response cue and asked if they understood it in the new context. Participants were assumed to have achieved insight if they initially failed to understand the sentence but understood it after the cue. Although it can certainly be argued that such a realization is not necessarily an insight, the investigators found a correlation between their participants' newfound understanding and activity in anterior cingulate cortex, an area known to mediate cognitive conflict (Carter et al., 2000) and left lateral prefrontal cortex, an area thought to mediate selection from among competing semantic alternatives (Thompson-Schill, D'Esposito, Aguirre & Farah, 1997).

In an ERP study in which 14 participants were given Chinese riddles and subsequently provided with a keyword that was consistent with the usual interpretation (no aha) or an unusual interpretation (aha), Mai, Luo, Wu and Luo (2004) found an ERP difference wave over Cz with peak latency of 380 ms that was source-localized to the anterior cingulate cortex. They interpreted their findings to mean that the anterior cingulate cortex was critically involved in breaking set in these types of insight problems, however they did not attempt to verify that insight had actually occurred.

Jung-Beeman and colleagues (2004) used both EEG and fMRI to study neural activity while people solved CRA problems. Participants were presented with the problems and indicated when they had reached solutions by clicking a mouse. Participants were also asked if they had experienced insight in solving the problems. Based on previous behavioral findings that demonstrated solution priming in the right hemisphere for both CRA problems (Bowden & Jung-Beeman, 2003b) and classic insight problems (Fiore & Schooler, 1998), the researchers predicted greater activity in the right anterior superior temporal gyrus (rASTG) when solvers used insight compared to noninsight. They identified the rASTG as a specific area of interest based on previous research (Meyer et al., 2000; Kircher et al., 2001) demonstrating its involvement in semantic integration, sentences, and complex discourse that requires recognition or computing of distant semantic relations. As predicted, using fMRI they found that the greatest difference in BOLD activation between insight solutions and non-insight solutions was in the rASTG (531 mm^3 at 44, -9, -9 in Talairach space). Activity also increased in this area when subjects first encountered each problem (469 mm3 at 41, -6, -12 in Talairach space). Jung-Beeman and colleagues (2004) also predicted that EEG would show sudden gamma band frequency activity in right anterior temporal lobe just prior to insight because activity in the gamma frequency has been associated with the activation of perceptual, lexical and semantic relationships (Tallon-Baudry & Bertrand, 1999; Pulvermuller, 2001). This prediction was also based on established correlations of gamma activity with BOLD response (Foucher et al., 2003; Laufs et al., 2003) and on the fMRI findings just described. In a different group of participants, Jung-Beeman and colleagues (2004) used EEG to record the expected gamma-band activity at anterior right temporal electrodes (T8) with no insight-related activity detected by the electrodes over the contralateral homologue (T7). The rapid onset of gamma activity occurred 0.3 s prior to when solvers indicated an insight solution by pressing a button. Insight solutions were also characterized by increased alpha activity in posterior visual cortical regions prior to the burst of gamma activity.

In another study using fMRI during solution of compound remote associates problems, Anderson and colleagues (2009) attempted to verify the roles of the lateral inferior prefrontal cortex (LIPFC) in memory retrieval and the dorsal anterior cingulate cortex (ACC) in sub-goal setting. They hypothesized that the process of searching for a solution to CRA problems would produce a sustained demand on a retrieval module (LIPFC) while the sub-goal module (ACC) would remain unchanged. After solution, they hypothesized that the ACC would increase activation while the LIPFC would decrease activation. fMRI confirmed their expectations. The investigators interpreted their findings to mean that ACC was processing solutions because it was more active when solutions were achieved. They challenged previous claims that ACC activation was associated with errors. Anderson and colleagues were primarily interested in discerning frontal cortical roles in insight, temporal areas were not considered to be an area of interest for this study.

Aziz-Zadeh and colleagues (2009) recently investigated the neural correlates of insight solutions to 5-letter anagrams using fMRI in healthy individuals with above average skill at anagram solution. They found that the anterior cingulate cortex (ACC), right prefrontal cortex and right pons were activated by insight solutions and deactivated by search solutions. They also found that the right temporal pole (Brodmann Area 38, located at MNI 42, 6, -40; an area quite proximal to the rASTG) was deactivated by search solutions and minimally activated by insight solutions. They speculated that the right PFC was involved in evaluation and meta-cognition of insight problem solving rather than the problem solving itself. They attributed monitoring and conflict resolution roles to the ACC. They also noted the right temporal pole's known role in processing idioms (Dronkers et al., 2004) and speculated that it may play a role in approaching problems in a more tangential manner. This finding is also in accord with previous findings of a role of right temporal areas in verbal insight problems (Kircher et al., 2001; Jung-Beeman et al., 2004).

The findings of studies investigating neural activity during solution of verbal insight problems are summarized in the following table:

Table 1. Summary of findings for neuroimaging studies of insight

Researchers	**Task**	**Time Course**	**Areas associated with insight**
Luo et al., 2003	Understanding incomprehensible sentences	During solution	ACC, left DLPFC
Mai et al., 2003	Chinese Riddles	During solution	ACC
Jung-Beeman et al., 2004	Compound Remote Associates	During Solution	ACC, right and left DLPFC, right ASTG
Aziz-Zadeh et al., 2009	Anagrams	During Solution	ACC, right PFC, right pons, right temporal pole
Anderson et al., 2009	Compound Remote Associates	During Solution	ACC, LIPFC

1.2.4 Neural Correlates of Insight Preparation

In addition to exploring neural correlates of the insight process, researchers have also begun to investigate whether different preparatory patterns of neural activity can predict whether problem solvers will adopt insight or analytic strategies. In studying mental preparation for different solution strategies, it is necessary to use problem sets of items that can be solved with either insight or analytic processes, such as CRA problems or anagrams.

Kounios and colleagues (2006) predicted that transient preparatory states just prior to problem presentation would predict whether problem solvers would use insight or analytic strategies to solve CRA problems. They used EEG and fMRI to record neural activity in two separate groups of participants as they solved problems. In the EEG group, midfrontal activity prior to problem presentation predicted eventual solution with insight. In a different group, fMRI identified the anterior cingulate cortex (ACC) as the likely source of that midfrontal activity. The ACC has been associated with conflict monitoring among competing responses. Because no obvious conflict exists prior to problem presentation, the researchers attributed the ACC's activity to its role in suppressing irrelevant thoughts (Anderson et al., 2004; Wyland et al., 2003), with the idea that such suppression may reduce internal interference, which would free the individual to engage in noninsight processing, a previously demonstrated (Schooler, Ohlsson, & Brooks 1993) requirement for insight. However, Kounios and colleagues (2006) speculated that the ACC is sensitive to cognitive conflict and in the case of a conflict between dominant and non-dominant solution paths, it may prepare a shift of attention to nonprepotent solutions or strategies in the right hemisphere after prepotent associations in the left hemisphere had failed to yield results (restructuring).

Kounios and colleagues (2006) also found that prior to seeing problems they would later solve with insight, participants showed heightened activity in bilateral temporal areas associated with semantic processing. They interpreted this to be preparation to retrieve both prepotent associates (which are mostly mediated by left posterior medial superior temporal gyrus activity), as well as weaker associations from the right posterior medial superior temporal gyrus.

1.2.5 A theory of mechanisms of verbal insight

In a series of papers, Mark Beeman, Edward Bowden, John Kounios and their colleagues (Jung-Beeman et al., 2004; Bowden et al., 2005; Kounios et al., 2006) have proposed various elements of a framework for understanding the neural underpinnings of verbal insight processes used during solution of compound remote associates problems. They have used EEG to gain a greater understanding of the time course and frequency ranges of the electrophysiological activity associated with insight and have used fMRI to localize the activity (compared to noninsight events).

In summary, greater activity in the anterior cingulate cortex and bilateral medial/superior temporal gyri (slightly skewed to the left) before problem presentation predicted solution with insight strategy (Kounios et al., 2006). For insight compared to noninsight solutions, after the problem was presented there was an increase in neural activity in right hemisphere anterior superior temporal gyrus. There was a transient increase in alpha power in right posterior parietal cortex lasting from 1.4 s to 0.4 s prior to when solution was indicated, followed by a rapid increase in gamma-band activity in the right anterior superior temporal gyrus 0.3 s prior to (Jung-Beeman, et al., 2004).

Kounios and colleagues (2006) theorized that the burst of gamma frequency activity is the insight and that it took participants about 0.3 s to realize they had reached the solution and to respond. They also theorized that the ACC prompted greater activity in bilateral medial/superior temporal gyri (via top-down control mechanisms), which bias participants to retrieve both prepotent associations (predominantly in left posterior M/STG) and weaker more distributed associations (in right posterior M/STG). During problem solution, prepotent candidate solutions are activated in left posterior temporal cortex. When such prepotent solutions fail to yield a solution (impasse), the ACC is hypothesized to shift attention to nonprepotent associations in the right posterior temporal areas. After external focus is reduced, as seen by increased right posterior parietal alpha activity, the sharp increase in right anterior superior temporal gyrus activity is the insight solution (Jung-Beeman et al., 2004). Kounios and colleagues (2006) speculated that insight strategies may be applied with limited frequency because the top-down component is too cognitively demanding to use for every problem in a series.

More recently, Cranford (2010) used fMRI to study insight and search strategies in the solution of CRA problems. Using methods that were substantially similar to previous investigations (Kounios et al., 2006, Jung-Beeman et al., 2004), with the additional question of whether the solution generated was the first solution considered, Cranford’s results implicated rASTG in the production of insight solutions. Separating insight responses into immediate and delayed, based on response time and whether the answer was the first one considered, his findings also suggest that immediate insights were associated with more rASTG hemodynamic activity compared to delayed insights. He concluded that rASTG activity predict *intuition*, which he defined as essentially the rapid ability to produce a correct solution on the first guess that is accompanied by a similar affective experience as insight. Although some investigators might dispute his requirement that an incorrect solution must be generated for an impasse to occur, as well as his characterizations of intuition, the finding that there was some sort of qualitative difference between rapid and delayed insight might be relevant to some of the results of this investigation with regards to the speed with which insight solutions are generated.

1.2.6 The next step: Testing theories of verbal insight

Although there is strong evidence that the neuroanatomical structures just described are active at various time points before and during insight processing, what role they play in the process is necessarily much more speculative. As tempting as it is to infer causation from neural activity that coincides with behavior, based on observations of neural activity alone it remains impossible to determine whether such activity contributes to the insight process or is merely epiphenomenal.

Causation can only be determined through experimentation. If the activity of select neuroanatomical areas that have been implicated in insight is manipulated during the problem solving process, and if such manipulation affects problem-solving behavior, one can infer a causal relationship between the manipulated area and insight processes. If excitation and inhibition of activity in an anatomical structure have opposite effects on one or more behavioral measures of insight, a causal relationship can be inferred with more confidence.

Recent innovations in the use of noninvasive electrical stimulation techniques have provided tools by which such experiments can be conducted. The following section will describe one such technique (direct current stimulation), review relevant studies of how it has been used in the study of cognition and insight, and discuss why it is the most appropriate stimulation methodology to use in an investigation of the neural mechanisms of insight.

1.3 Neural Stimulation

There are a variety of methods to directly alter neuronal electrophysiology in an immediate and noninvasive fashion in conscious humans. Additional new techniques for applying these technologies, as well as whole new methods for delivering stimulation, seem to be reported with increasing frequency (see Huang et al., 2009 for a review of new methodologies and Zaghi et al., 2010 for a discussion of mechanisms of action). The most well researched methods are transcranial magnetic stimulation and transcranial direct current stimulation. This section will describe direct current stimulation, the technique used in this experiment, and explain why it was chosen over transcranial magnetic stimulation.

1.3.1 Transcranial direct current stimulation

Transcranial direct current stimulation (tDCS or DCS) is a method of painless noninvasive cortical stimulation. It has a long history of use dating back to the early 1800s (Priori, 2003). Modern tDCS relies on a low intensity current to alter membrane potentials and affect neuronal excitability. When direct current is applied to neurons, it can both enhance (anodal) and diminish (cathodal) cortical activity and excitability (Nitsche et al., 2008). Because tDCS does not yield rapid depolarization and action potentials, it is considered to be a neuromodulatory intervention.

By studying input-output curves and motor thresholds as parameters of cortico-spinal excitability, Nitsche and colleagues (2005) determined that anodal tDCS enhanced cortico-spinal excitability after extensive stimulation, but not during stimulation. Cathodal stimulation reduced excitability during tDCS and after stimulation ended. Although this research was conducted in motor cortex, it may have relevance for online effects of tDCS in temporal cortex. Specifically it could explain a lack of behavioral effects of anodal stimulation during the first few minutes of stimulation.

As for offline effects, stimulation length strongly correlates with the duration of tDCS-mediated after-effects on behavior (Nitsche & Paulus, 2000; 2001; Nitsche et al., 2005). The effects of 10-30 min of tDCS stimulation on motor-evoked potentials in the motor cortex can last for 5 h and longer (Nitsche & Paulus, 2000). It has also been shown that in both motor cortex (Nitsche & Paulus, 2001) and occipital cortex (Antal et al., 2004), a shorter period of cathodal stimulation, compared to anodal stimulation, is required to achieve effects on behavior that last for 60 minutes after stimulation ends.

Animal studies have shown that deeper cortical sulci (with differently oriented neurons) showed opposite affects on neural activity in response to anodal and cathodal stimulation (Creutzfeldt, Fromm & Kapp, 1962). The magnitude, direction and duration of effects of tDCS stimulation on behavior may critically depend on the type and location of cortical tissue that is being stimulated (Radman, Ramos, Brumberg, & Bikson, 2009). Most of the parametric studies of tDCS effects have been conducted in motor cortex, so researchers should not assume that stimulation will achieve similar magnitude and direction of effects on cortical activity when applied in areas that may have different cytoarchitecture.

In general, the lasting effects of tDCS are not mediated through lasting changes in membrane potentials. This was demonstrated in an experiment in which hypothermia was used to completely cancel electrical brain activity (in the rat) and the changes remained (Gartside, 1968). It has been proposed that these are LTP/LTD-mediated changes (Hattori et al., 1990; Moriwaki, 1991; Islam et al., 1995; Huang, Rothwell, Edwards, & Chen, 2008). Because changes in cortical excitation are mediated through LTP/LTD-like changes, it is possible that changes in behavior elicited by stimulation may be reversible via stimulation with the opposite electrode, although there has been little research done to verify that hypothesis.

With repeated sessions of stimulation these changes can be stable for days (Marshall et al., 2004; Fregni et al., 2006b; Roizenblatt et al., 2007), weeks (Fregni et al., 2006a; Boggio et al., 2007; Boggio et al. 2008) and even months (Rigonatti et al., 2008; Reis et al., 2009) after the end of stimulation, which makes tDCS an enticing technology for both clinical and research applications.

The safety profile for tDCS has been remarkable, considering that thousands of people have participated in such research to date. There have been no serious long-term adverse events of tDCS reported in the literature. The most common side affect of tDCS is an experience of tingling (76% of participants) at the stimulation site that can turn to itching (68% of participants) and or burning (54%) and sometimes pain (25%) (Kessler, Turkeltaub, Benson & Hamilton, 2011). There have also been some reports of mild headaches (10% of participants, mostly in patient groups rather than healthy groups) and temporary drowsiness (30% of participants) (Poreisz, Boros, Antal and Paulus, 2007. Headaches and drowsiness seem more commonly the result of frontal lobe stimulation (Fregni et al., 2008; Boggio et al, 2007). Many tDCS experiments report no adverse events at all (Nitsche et al., 2008).

1.3.2 Why tDCS was the best stimulation technique for this investigation

As discussed above, direct current is not the only method of delivering noninvasive stimulation, there is also transcranial magnetic stimulation (TMS). There are several practical concerns that made DCS a better tool for this investigation (for a comprehensive review comparing tDCS to TMS, see Priori, Hallett, & Rothwell, 2009). The most important advantage is that there is a reliable sham condition for DCS (Gandiga, Hummel, & Cohen, 2006). With TMS, the sensations experienced during stimulation are so distinct that only a TMS-naïve participant is fooled by the sham condition. For the purposes of this experiment, in which performance during stimulation was compared to sham, this quality was essential. Also, unlike TMS, which induces neuronal action potentials in targeted tissue regardless of individual neuronal involvement in the behavior of interest, DCS is a neuromodulatory technique that alters the likelihood of action potentials in affected tissue. This may give DCS an advantage in terms of ecological validity because, rather than serving a purely disruptive function on underlying cortex by causing uniform firing of action potentials regardless of tissue type and function, DCS alters the probability that underlying neurons will fire action potentials. Another advantage has to do with the target cortical area, namely the right anterior superior temporal gyrus (rASTG). When applied to the temporal cortex, TMS can cause somewhat painful sensations because there can be greater stimulation of peripheral nerves and muscles of the scalp, while DCS has not been reported to cause more irritation when applied over temporal cortex than in other cephalic locations (Nitsche et al., 2008).

There are also practical advantages of DCS, such as the requirement for TMS that a physician be in the room in case there is a seizure or other adverse event. Because serious adverse events have not been known to occur with DCS, emergency medical precautions are not as rigorous. For example, the University of Pennsylvania's protocol requires that a neurologist be present or on-call such that they can be at the participant's side in less than five minutes. Another practical concern with TMS is the requirement that the participant have an MRI, so that focal stimulation can be delivered with stereotaxic positioning systems. DCS requires no previous imaging and can be easily positioned within minutes with the 10-20 international electrode positioning system (Jasper, 1958). Although in some investigations the excellent spatial resolution of TMS is an advantage, for the purposes of this study, in which potential target areas mediating the behavior of interest may be larger than the area stimulated by TMS, the relatively diffuse stimulation of DCS is preferred.

Although this experiment was largely an investigation into the neural correlates and behavioral qualities of insightful problem solving strategies, the results reported here could eventually lead to clinical applications for stimulation of insight. Considering future clinical utility, DCS has several enormous advantages as a potential clinical tool: it is much more portable, much less expensive, and much safer than TMS.

Table 2. Characteristics of TMS and DCS

	TMS	**DCS**
Type of Stimulation	Induced by magnetic field	Direct current
Spatial resolution	10-20 mm	5 cm
Online Temporal Resolution	Instant	Within seconds
Offline Temporal Resolution	Dose dependent	Dose dependent, can be within 3 minutes
Range	2-3 cm	Unknown
Mode of Action	Virtual lesion (temporary disruption of functioning	Neuromodulation (alters membrane potentials)
Increase Excitability?	Yes (10-20 Hz)	Yes (anodal stimulation)
Decrease Excitability?	Yes (1 Hz)	Yes (cathodal stimulation)
Sham Control?	Ineffective	Yes
Safety Profile	Can cause seizures, requires presence of a physician	No serious adverse events, requires physician to be within 5 minutes
Targeting system	Neuroimaging system using MRI data and stereotaxic positioning system	10-20 electrode placement system

In summary, direct current stimulation can effectively establish functional relationships between targeted neuroanatomical sites and behaviors of interest, and for the reasons outlined above it was the preferred technique for this investigation. The following portion of this section will review research in which investigators have used direct current stimulation to explore functional relationships in temporal cortical areas. These studies are relevant given that we chose to stimulate the right anterior superior temporal gyrus in this investigation.

1.3.3 Studies of temporal lobe stimulation with tDCS

Up until the past few years, the vast majority of studies using tDCS had targeted motor cortical areas. This may be because many researchers using tDCS have a background in TMS, which uses motor evoked potential (MEP) as a reference for individual stimulation thresholds. Of course, motor cortex is also an attractive target for researchers in the field of stroke rehabilitation. Consequently, many of the pioneering parametric studies of tDCS, notably those of Nitsche and colleagues (2000; 2001; 2003a; 2003b; 2005), used effects on MEP as an easily verifiable outcome that was specific to the individual. Thus if tDCS was shown to decrease the threshold of TMS required to achieve an MEP, it was seen to be excitatory and if it increased the threshold it was inhibitory.

However, after some clinically significant successes in increasing motor function (see Nitsche, 2008 for a review), in the past 5 years researchers have conducted an increasing number of studies targeting areas of frontal, occipital and temporal cortex. Because the research discussed here targeted the right anterior superior temporal gyrus, in order to explain why some choices were made as to duration, location and intensity of stimulation, it will be instructive to review some successful protocols that generated behavioral effects by stimulating areas of temporal cortex relevant to language processing.

In a within-subjects design, Floel and colleagues (2008) gave anodal, cathodal and sham tDCS (1 mA for 20 min) to healthy participants on three separate sessions while they attempted to acquire a novel lexicon. They targeted left superior temporal cortex (Wernicke's area) due to its known critical involvement in semantic processing. In each session, language learning began during active stimulation and continued for 10 min after (offline). They found that anodal stimulation significantly accelerated language learning by the end of active stimulation, while cathodal stimulation did not inhibit language acquisition. The authors noted that their finding is in accord with previous research that showed no effects of cathodal stimulation on motor learning (Nitsche et al., 2003b).

Boggio and colleagues (2009a) were interested in reducing false memories by applying stimulation during both the encoding and retrieval phases. Their three stimulation conditions were: 1) 10 min of 2mA anodal tDCS on left anterior temporal lobe coincident with cathodal stimulation on right anterior temporal lobe, 2) 10 min of 2mA anodal stimulation of left anterior temporal lobe only, and 3) sham stimulation for 30 s. They found that both of the first two conditions reduced false memories but that sham had no effect. The investigators attributed the reduction of false memories to a diminished reliance on gist in encoding and retrieval, a function that is mediated by the left ATL. In a previous study, Gallate and colleagues (2009) found that inhibitory 1 Hz rTMS to left ATL reduced false memories. However, in this study typically excitatory anodal tDCS had an even stronger inhibitory effect. They attributed the unexpected effect of anodal stimulation to the fact that tDCS stimulation is more diffuse than rTMS stimulation. Because it is less focal, tDCS stimulation increased activity in a large cortical area around ATL, which competed with the semantic center and de-emphasized the efficiency of the main semantic processing circuits, thus increasing the tendency for literal interpretation and reducing false memories. In addition to the stimulation methodology, which is important to consider when selecting methods of temporal lobe stimulation, and the encouraging demonstration of an effect of tDCS on semantic processing, Boggio and colleagues' interpretation of the effects of stimulation may also be relevant to this research. The fact that unexpected and opposite effects of anodal stimulation were seen in Boggio's research suggests that the use of tDCS to stimulate rASTG could have caused a similar center-surround effect that may have led to inhibition of the target area when excitation was expected, or excitation when inhibition was expected.

A particularly relevant study for the research discussed here is one by Chi and Snyder (2011) in which the investigators stimulated the right and left anterior temporal lobes (ATL) simultaneously with tDCS in order to enhance the insightful solution of a matchstick addition problem (see figure 2, Appendix A). In a between-subjects design, 60 participants practiced 27 type-1 matchstick addition problems that do not require insight, as part of a "mental set" phase. After training on the problems, participants were given online stimulation for 5 minutes before being given12 minutes to solve two additional problems (type 2 and type 3; figure 2, Appendix A). The participants were divided into 3 groups, one group received cathodal stimulation to the left ATL and simultaneous anodal stimulation on the right ATL (L-/R+), another received the opposite montage of anodal stimulation to the left ATL and cathodal stimulation to the right ATL (L+/R-), and the last group received sham stimulation. They found that participants who received both sham and L+/R- bilateral stimulation solved the more difficult problem about 20% of the time with little additional progress after about 2 minutes. However, approximately 60% of the group receiving anodal stimulation to the right ATL and cathodal to the left ATL (L-/R+) solved the difficult type-2 problem within 6 minutes, a significant difference (p=.022). There was a similar advantage to the easier type-3 problem. With sham stimulation, about 45% of participants solved the problem, while with (L-/R+) about 85% solved the problem (p=.019). Unfortunately, due to the use of bilateral stimulation, interpretation of the mechanisms by which stimulation enhanced problem solution is problematic. The authors acknowledged that interpretation became more difficult because the reference electrode was not inert. They suggested three possible explanations: 1) Right-hemispheric dominance was enhanced via both direct anodal stimulation and diminished contralateral inhibition of the right hemisphere coming from the left hemisphere, due to cathodal stimulation of the left hemisphere. The left-to-right shift of hemispheric dominance may have increased participants' ability to process novel cognitive situations and may have led them to be less constrained by the cognitive routine instantiated during the training phase. 2) An alternate explanation was that the inhibition of the left ATL led to a less top-down influenced (hypothesis driven) cognitive style, which reduced the influence of mental set. 3) A final suggestion was that stimulation of the right ATL, which is associated with novel meaning and insight, simply improved the likelihood that participants would reach an insight to break their mental set.

1.4 The current study: A rationale for DCS of rASTG

This section will explain the rationale followed here for using direct current stimulation to investigate functional mechanisms of insight in problem solving. It will discuss the anatomical regions that were considered as targets of stimulation (based on the research that has been reviewed) and includes the rationale for targeting the rASTG. The rationale will conclude by examining reasons why it was important to explore a possible relationship between insight and recall. It will also examine how the research improved our knowledge of both insight processes and the effects of direct current stimulation in the temporal cortex.

1.4.1 Clarifying the neural mechanisms of verbal problem solving with insight

Although great progress has been made in building a theory of the functional anatomy of verbal insight, there is still a great deal of uncertainty. Direct current stimulation has provided an opportunity to test the theories that neuroimaging research has helped develop.

Neuroimaging findings regarding insight processing consistently implicate both anterior cingulate cortex and right superior temporal gyrus. Although medial frontal lobe functions (ACC) are implicated in both top-down preparation for insight and internal attention switching during insight processing, the numerous other executive functions of the frontal areas (selective attention and sustained attention, among others) make it difficult to disentangle the roles of its many constituent parts in a complicated problem-solving task. In contrast to the multipurpose role of ACC in insight, the role of the rASTG appears to be more clearly specified. A significant and growing literature details the many contributions of right hemisphere processing to the kind of distal semantic association tasks likely to be useful in the solution of verbal insight problems. The findings of Jung-Beeman and colleagues (2004) strongly suggest that the role of the rASTG is to somehow finalize processing related to insight solutions to verbal problems by bringing relevant nonprepotent associations to conscious awareness. Because theory more clearly delineates the role of rASTG and because direct current stimulation cannot penetrate deeply enough to reach ACC, the rASTG was the most appropriate target for exploration of verbal insight with direct current stimulation.

1.4.2 Improving recall with insight

Beyond increasing our understanding of the processes involved in verbal problem solving, there is some evidence that insight solutions of verbal insight problems (anagrams) are recalled more readily than non-insight solutions (McCabe, unpublished). Auble, Franks and

Soraci (1979) studied recall of incomprehensible sentences followed by words to cue understanding (and insight). They found that sentences that were difficult to understand prior to cuing were later recalled better than both the same sentences without cue words, and more easily understood sentences with and without cues. Although they merely assumed that insight had occurred, this scenario does seem likely to illicit some degree of insight, so the suggestion of a recall benefit is intriguing. The investigators speculated that the ‘aha’ effect may have facilitated recall because the unusual qualities of the insight experience provided a much more distinct retrieval cue. The insight process in this paradigm may also rely on the generation of a representation that meets task requirements (comprehensibility) and hence recall may benefit from deeper integration (Auble, Franks & Soraci, 1979). Their findings are also somewhat qualitatively different from those of McCabe, who found a benefit of insight on recall of problem solutions, not the problems themselves.

It is possible that the effects described above can be attributed to the generation effect, a well-established phenomenon by which recall is facilitated for information that was participant-generated versus experimenter provided. The generation effect has been shown with a variety of stimuli ranging from word fragments to math problems (Jacoby, 1978; Roenker, Wenger, Thompson, & Watkins, 1978; Slamenka & Graf, 1978; Johns & Swanson, 1988; McNamara & Healy, 1995). However, the generation effect is insufficient to explain McCabe’s findings because participants in that study generated both insight and analysis solutions.

In an effort to duplicate the ‘Aha’ effect on recall while discounting the generation effect, Wills, Soraci, Chechile and Taylor (2000) conducted an experiment in which participants were asked to complete connect-the-dots pictures, some of which had been pre-identified and some of which had not. Recall for pictures in the later group was higher, an effect that the investigators attribute to the ‘aha’ effect. There was no benefit for recognition memory. Unfortunately, they again did not assess if insight had occurred. It is also debatable whether connect-the-dots stimuli are truly participant-generated. Despite these methodological flaws, the ‘aha’ affect on recall was again demonstrated, this time with a different type of stimulus.

The supposed recall benefit of insight is somewhat counter-intuitive considering reports that information about insight solution processes is unavailable to introspective techniques. Integration and elaboration of information is generally considered to be beneficial to recall (Emilien, Durlach, Antoniadis, Van Der Linden, & Maloteaux, 2004). It is possible that the well-understood benefits of elaboration for memory (typically accessible to meta-cognition and presumably mediated via left hemisphere processes and fine semantic distinctions) may not be unique in this regard. Perhaps there is a similar parallel benefit to recall via elaboration of more coarse distinctions or unconscious processes in the right temporal lobe.

A somewhat more likely scenario is that the beneficial effects of insight on recall can be attributed to insight’s emotional quality. The beneficial effects of emotion on memory are well established (McGaugh, 2003). However, the possibility that the affective qualities of the insight experience continue to occur with sufficient strength, trial after trial, to provide a consistent benefit for recall seems unlikely. Although at present the mechanism by which insight may improve recall is poorly understood, the finding could be appealing from a clinical viewpoint. Replicating McCabe’s findings in anagrams with similar findings using CRA problem solutions could motivate future researchers to improve insight in normal populations and clinical populations in order to compensate for verbal and/or visual memory deficits. Because testing free recall of participant-generated solutions of CRA problems and comparing recall of solutions generated with insight as opposed to analytic processes could be informative in this regard, this investigation was designed to test recall of CRA problem solutions.

1.4.3 Adding to extant literature on stimulation effects

Studies about the time course of behavioral effects of DC stimulation are much needed in the literature. While there have been a few parametric studies of DC effects in motor cortex, there are no such studies in temporal cortex and there is reason to believe different cytoarchitectures may respond differently to DC stimulation (Radman, Ramos, Brumberg, and Bikson, 2009). While this research was primarily designed to investigate the effects of rASTG stimulation on insight processes, because stimulation is discontinued part way through the series of CRA problems, there is an opportunity to compare its direct effects on problem solving strategies with lingering effects after stimulation ends.

1.4.4 Objectives

This research attempted to add to extant literature in the areas of human insight during problem solving, declarative memory, and direct current stimulation. The study was designed with the following two goals in mind:

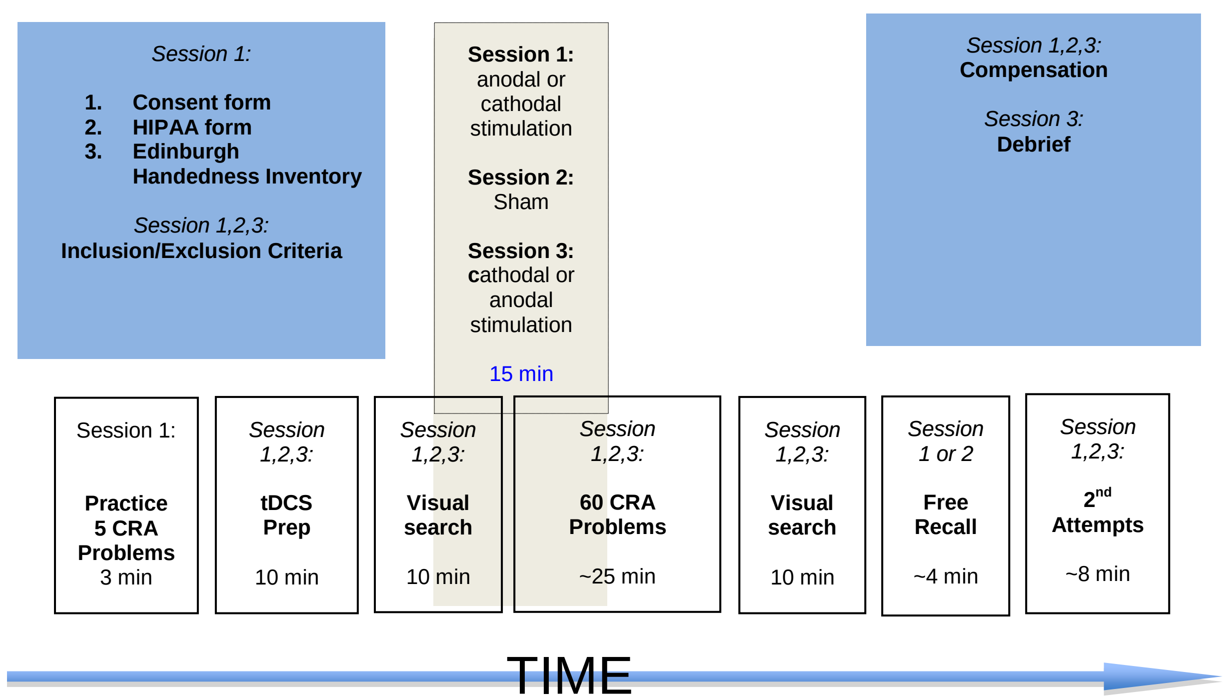
- Goal 1: Explore the right ASTG's role in insight solutions of CRA problems.
- Goal 2: Explore and the insight-recall relationship and explore the degree to which stimulation moderates that effect.

METHODS

2.1 Overview

This investigation sought to determine if altering activity in right anterior superior temporal gyrus affected problem solvers' use of insight solution strategies. It also sought to explore the effects of solution strategy on declarative recall and to see if direct current stimulation affected that relationship. During each session, participants engaged in a visual search task for 10 minutes and then tried to solve CRA problems while receiving active stimulation or sham stimulation. After attempting to solve 61 CRA problems, participants engaged in the visual search task a second time. After visual search, participants' recall of correct CRA solutions was tested for only 1 of the three sessions. Finally, participants tried again to solve the CRA problems they did not solve previously. (Data, analyses and discussion related to solving CRA problems after a period of incubation were part of a separate experiment and will

Figure 4: Protocol



not be discussed here.) Multivariate analysis of variance (MANOVA) was used to examine if stimulation affected insight solution strategies along with planned comparisons between stimulation types using paired-samples t-tests and repeated-measures ANOVAs when using covariates. Paired-sample T-tests were used to explore the relationship between participants' use of insight and their declarative recall.

2.2 Participants

Participants were 28 students from the University of Pennsylvania community. The participants' mean age was 24.6 (SD = 6.47) and they had a mean of 16.1 (SD = 2.39) years of formal education. Participants were right handed (as verified by scores of 16 or more on a scale of 1-20 on the Edinburgh Handedness Inventory (Chapman & Chapman, 1987). There is ample evidence that language is predominantly lateralized to the left hemisphere in right-handed individuals, but in left-handed and ambidextrous individuals, lateralization of language and other cognitive functions is less certain (Bryden, 1982), therefore left-handed individuals were excluded. Participants were excluded if they had a diagnosed history of neurologic or psychiatric disorders, such as psychosis, any affective disorder, or any type of neglect syndrome. Participants were excluded if they had a history of substance abuse. Participants taking medications (anticonvulsants, sedative/hypnotics, or anti-psychotic medications) that may alter neuronal membrane stability were excluded due to uncertain or variable effects of stimulation in combination with such medications (Liebetanz et al., 2002; 2003; Nitsche et al., 2006; 2004a; 2004b; 2004c). Although there has been no indication that tDCS alters seizure risk, participants with a history of seizures were excluded because the issue has not been fully investigated. Although there is no known indication that tDCS is a risk to the fetus, pregnant participants were excluded because the issue has not been fully investigated. Female participants were asked to undergo a pregnancy test at the time of testing. Prisoners were not recruited, nor were participants under the age of 18. Because this study assessed problem solving of remote associates problems, which require mastery of English language, participants who were not native speakers of English were excluded. Participants were required to have normal or corrected-to-normal vision because stimuli will be presented on a computer screen.

Participants received $20/hour for each of the three sessions and typically received a total compensation of approximately $90. The funding for the study was provided in part by a grant from the American Psychological Association and the rest came from the personal funds of the author.

2.3 Recruitment

Approval to conduct the study was obtained from the University of Pennsylvania as part of protocol 809185: “Transcranial Direct Current Stimulation Investigations of Cognition and Action in Normal Subjects.” The protocol was previously approved on 8/10/2009 by the University of Pennsylvania’s Institutional Review Board of the University of Pennsylvania with H. Branch Coslett, MD, as primary investigator, and approval was renewed on December 9, 2010.

Participants were recruited from the undergraduate and graduate student population of the University of Pennsylvania via databases of previous participants in transcranial stimulation studies and via the Experimetrix website of the University of Pennsylvania Department of Psychology, in experimental database of participants that is limited to undergraduates, graduate students and research professionals in the University of Pennsylvania community.

After signing a consent form (Appendix F), all participants were asked to sign a form indicating that they still met inclusion/exclusion criteria prior to each of the three sessions

(Appendix C). They were given the Edinburgh Handedness Inventory (Chapman & Chapman, 1987; Appendix E) to verify that they were right-hand dominant during recruitment.

Participants were randomly allocated to one of two counter-balanced stimulation sequences. Fourteen participants received anodal stimulation on session 1, sham stimulation on session 2, and cathodal stimulation on session 3. The 14 participants allocated to the alternative sequence received cathodal stimulation on session 1, sham stimulation on session 2 and anodal stimulation on session 3.

2.4 Stimuli

2.4.1 CRA problems

The compound remote associates problems were taken from a list of 144 problems that was published with normative data about solution rates and solution times (Bowden & Jung-Beeman, 2003a). Those researchers also recorded solution percentages within 30 seconds for an additional group of 39 more CRA problems, which were also used. The problems were sorted into three groups according to difficulty. There were 65 easy problems (>60% solution rate within 30 seconds), 69 medium problems (30-59% solution rate within 30 seconds), and 48 hard problems (<30% solution rate within 30 seconds). The problems were distributed as evenly as possible so that there are approximately equal numbers of easy, medium and hard problems presented on each of the stimulation sessions. Problems were also arranged so that they alternate in difficulty as much as possible to avoid frustrating participants. Problem difficulty was also divided so that it was equal in the first 40% of problems compared to the last 60% of problems in each session, to allow effective comparison of online and offline stimulation within sessions.

The CRA problem sets were designed to take sufficient time so that for the first 10 min of problem solving, participants are receiving online stimulation. Offline stimulation effects were expected to last for the remainder of the solution time (Nitsche & Paulus, 2001). This period of solution time was determined by both participants' response times and a 30-second timeout after failure to respond. Although there was some concern within the committee about the possibility that participants would become irritated with 30-second periods prior to timeout, the 30-second limit was chosen because it was calculated that with a 15-second timeout period, completion of an entire set of 61 problems would take an average of about 15 minutes, which would make it difficult to compare online and offline stimulation effects with only 5 minutes worth of offline problems on the back end of the set. It was also thought that based on the solution rates reported in Bowden & Beeman (2004) that the additional time would lead to a greater number of solutions and more data points to analyze.

2.4.2 Visual Search

The search task (Ellison et al., 2004) involved rapid serial search for a single object among an array of similar objects, such as an 'L' among an array of L-shaped objects rotated 180 and 270 degrees (figure 3, Appendix B). Participants were required to indicate if the target item was on the screen as fast as they could. Five minutes prior to the onset of stimulation (or sham), the participants began the visual search task, which they continued for 10 minutes (until stimulation had been on for 5 minutes).

The visual search task helped control for pre-stimulation activity. There is evidence that prior states of cortical activity may have different affects on response to tDCS (Antal et al., 2008). According to the Bienenstock-Cooper-Munro (BCM) rule, high levels of previous activity favor overall synaptic depression and low levels of activity favor potentiation (Bienenstock, Cooper, & Munro, 1982). Although it is difficult to predict how visual search activity will impact direct current's effects on CRA problem solving, it is important that participants are doing the same activity prior to the different trials of stimulation and subsequent problem solving. The visual search task also allowed for conservation of CRA problems and helped maximize the size of the CRA problem set in each stimulation condition. Had stimulation begun coincident with CRA problem solution, early results would need to be discarded due to participant preoccupation with stimulation onset.

The primary function of the second visual search task, also lasting 10 minutes, was to serve as a non-interfering delay task that prevented rehearsal of solutions as much as possible between the initial presentation of CRA problems and the recall phase. Due to its nonverbal nature, the visual search task should not have interfered with the verbal declarative memories of interest, which will help in achieving aims 2 and 3.

2.5 Direct current stimulation methods

tDCS is usually applied via two electrodes wrapped in saline-soaked sponges that are strapped to the scalp and placed according to the 10-20 international system for EEG electrode placement (Jasper, 1958). The active electrode is positioned over the cortical area of interest and a reference electrode is typically positioned over an area thought to be uninvolved with the behavior of interest. The current is applied constantly and it flows from the cathodal electrode to the anodal electrode (Nitsche et al., 2008), either of which can be used as the active or reference electrode. TDCS can be applied *online*, while patients are engaged in behaviors of interest, or *offline* for a period prior to the behavior of interest.

2.5.1 Stimulation strength

The strength of tDCS stimulation is determined by the current density (mA/cm^2), which determines the strength of the electrical field that is induced (Purpura & McMurtry, 1965) in a particular region. Current density is a measure of current per unit area and is typically measured in microamperes/cm^2. In most investigational uses of tDCS, current ranges from 1 mA to 3 mA. and electrode size, typically measured in square centimeters ranges from 5-100 cm^2. Past research has shown that in motor cortex, current density can be instrumental in determining if there is an effect of tDCS on behavior (Nitsche, 2000; 2003a, 2007). Such has also been shown to be the case in temporal cortex, for example Boggio and colleagues (2006) saw an effect of anodal tDCS at 2 mA on working memory but not at 1 mA with the same size electrode (35cm^2). The current density used in previous studies that have shown changes after temporal lobe stimulation has ranged from .029 microamperes/cm^2 (1 mA) (Floel et al., 2008) to .057 microamperes/cm^2 (2 mA) (Monti et al., 2007; Boggio et al., 2006; Boggio et al., 2009).

In this study, tDCS current strength was applied at 1.5 mA for 15 minutes (or 15 seconds in the case of the sham condition). The electrodes had a contact size of 25 cm^2, so the total current density at the skin was .060 microamperes/cm^2, a value well within safety guidelines (Bikson, Datta & Elwassif, 2009; Poreisz, Boros, Antal & Paulus, 2007). Sham stimulation was at 1.5 mA (anodal) and current was delivered for approximately 10 seconds at the beginning of the sham condition. In all three sessions, current was gradually extinguished in a sine curve over the course of 5 seconds, a procedure that at 1.5 mA has been shown not to elicit perceptions of tingling/itching (Hummel et al., 2005; Nitsche et al., 2003a). The brief delivery of current in the sham condition typically produces sensations that mimic the tingling/itching sensation that participants experience at the start of actual stimulation. The tingling sensation experienced in actual stimulation typically fades within the first 15 seconds, therefore participants cannot tell sham from actual stimulation (Gandiga, Hummel, & Cohen, 2006). Although it is thought that some participants can tell sham from active stimulation based on their experience of side effects (Kessler, Turkeltaub, Benson, & Hamilton, 2011), no participants commented about whether they felt they were experiencing sham or actual stimulation. Some participants described feeling a slight itching during stimulation, a sensation that faded after a few seconds.

2.5.2 Reference electrode location

When deciding where to place the reference electrode, two factors were considered. First, the reference electrode in tDCS is active. So if the target area is receiving anodal stimulation, the area beneath the reference electrode receives opposite-pole cathodal stimulation. (And if the target receives cathodal stimulation the reference electrode delivers anodal stimulation.) Therefore, it was vital that the reference electrode be positioned over an area thought to be inert as far as the behavior of interest.

Also, the direction in which the current flows from beneath the target site (determined by the location of the reference electrode) may determine its affect on behavior (Nitsche & Paulus, 2000; Priori, Berardelli, Rona, Accornero, & Manfredi, 1998; Antal, Kincses, Nitsche, Bartfai, & Paulus, 2004). In an early parametric study that remains one of the few parametric studies of tDCS effects, Nitsche and colleagues (2000) found that the effects of stimulation of motor cortex could depend completely on reference electrode placement. Antal and colleagues (2004) found that changing the placement of the reference electrode could eliminate the behavioral effects of occipital (visual) cortex stimulation. This may be due to the orientation of the target neurons or axons in the cortical area in question and how that orientation can respond differently depending on the direction of current flow (Creutzfeldt, Fromm, & Kapp, 1962; Radman, Ramos, Brumberg, & Bikson, 2009). Unfortunately, there has been very little systematic research about the effects of reference electrode location. For this experiment, the right mastoid was used as a reference site because it is not considered to be located above a cortical area that would affect the behaviors of interest for the experiment and it was thought that such a proximal reference electrode location would minimize difficult to predict shunting of current through the brain as a whole (Sadleir, Vannorsdall, Schretlen & Gordon, 2010).

2.5.3 Onset and duration of stimulation effects

Understanding that differences in the time course of stimulation (whether it was online or offline) may determine the valence and magnitude of its effects on behavior was a crucial aspect in the interpretation of the results. Therefore a brief review of what is known about onset and duration of DCS effects will follow.

In this study, active stimulation at 1.5 mA lasted for 15 minutes. Published stimulation times for a single session of tDCS have ranged from a few milliseconds to as long as 40 min

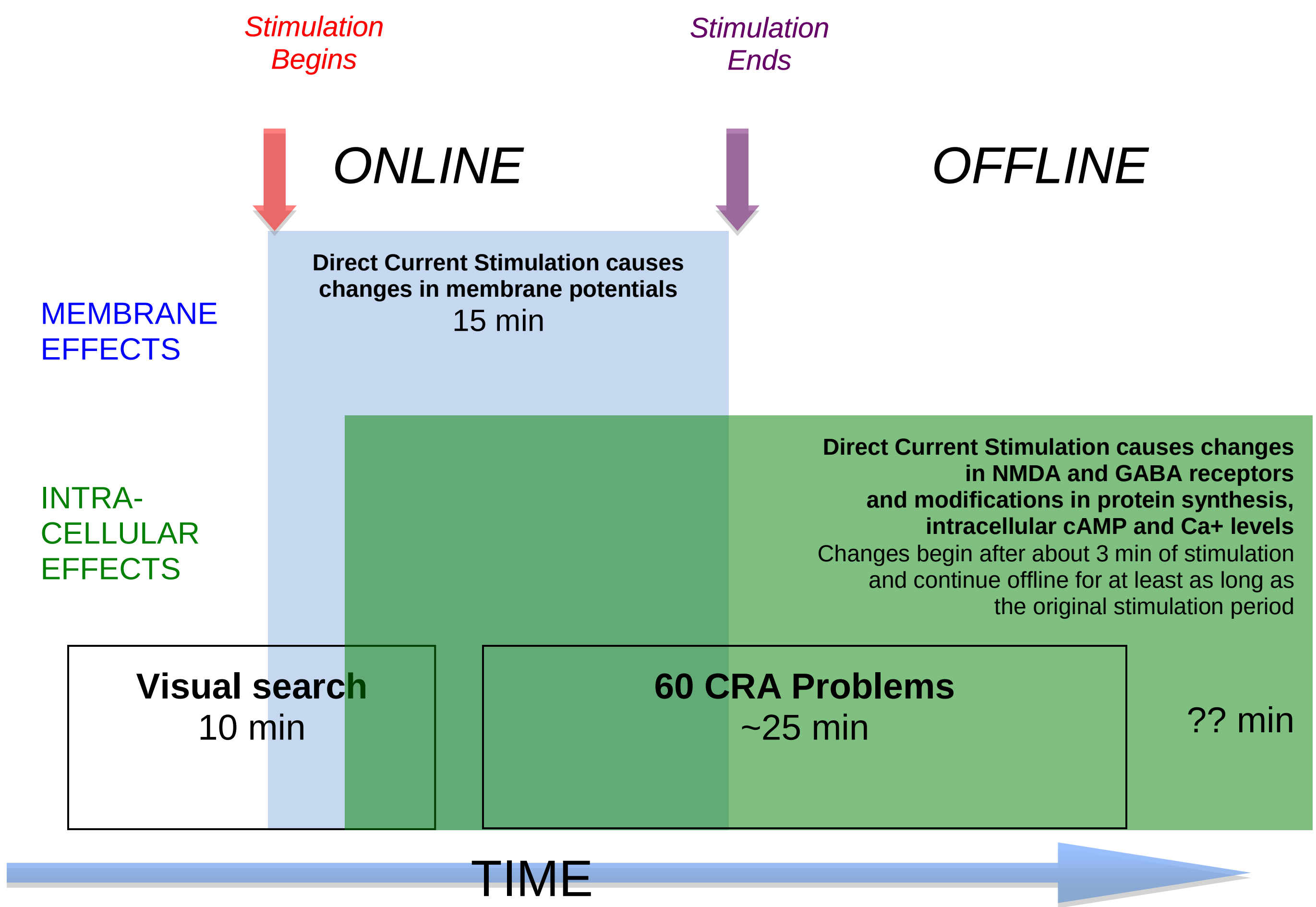


Figure 5: Time course of stimulation effects

(Huey et al., 2007); the duration of stimulation used here is typical of most tDCS studies conducted to date. Because the stimulation time was 15 minutes, potential effects of stimulation on behavior may have been mediated by both polarity-specific shifts of membrane potentials via voltage gating (Nitsche, 2001), which last for the duration of stimulation, and more lasting changes in receptor efficacy (Hattori et al., 1990; Moriwaki, 1991; Islam et al., 1995; Huang, Rothwell, Edwards, & Chen, 2008) and protein synthesis, the onset of which are delayed by a few minutes, but which are thought to last offline for a period of time at least as long as the stimulation period (figure 4). The term “online” can be misleading because there are the initial effects of stimulation on neuronal membrane polarities (in blue below) during the first few minutes of stimulation, and then there are the intracellular effects that begin to occur later. Both of these effects are presumed to be occurring during stimulation. To what degree these stimulation effects differ in altering behavior is unknown.

The time course for DCS effects on cortico-spinal excitability is thought to be very rapid, on the order of seconds (Nitsche et al., 2000; Furubayashi et al., 2008). Such excitability depends on sodium and calcium channels and on polarity-specific shifts of the resting membrane potential. Once stimulation begins, online effects of stimulation that are mediated by shifts in resting membrane potential occur almost instantly and likely last for the duration of stimulation. DCS has been shown to alter motor evoked potentials in motor cortex within 4 s (Nitsche et al., 2000). After stimulation of motor cortex, changes in reaction time on a serial reaction time task also occur very rapidly (Nitsche et al., 2003a), as do changes in the ability to perceive phosphenes prompted by stimulation of occipital cortex (Antal et al., 2004). Although there has been little done to examine the speed with which such changes occur in temporal cortex, there is little reason to believe that it would be significantly different. Because stimulation began about 5 minutes after participants started the visual search task, one would expect any changes in search behavior that are caused by stimulation's effects on resting membrane potential to become apparent within the first few seconds of stimulation. Behavioral effects of DCS-mediated membrane polarity shifts, if they occur, would be expected to affect behavior in the final minutes of the visual search task and the first 10 minutes of CRA problem solution. Because changes in membrane potential are transient, these short-lasting and rapidly fading (within seconds) effects are truly online-only.

In addition to the direct effects of stimulation on resting membrane potential, more lasting effects of stimulation are mediated through efficacy changes in N-methyl-D-Aspartic acid (NMDA) receptors and gamma-aminobutyric acid (GABA) receptors (Liebetanz et al., 2002; Nitsche et al., 2004c; 2008). Studies in rats have shown that the lasting effects of tDCS are dependent on protein synthesis (Gartside, 1968) and they coincide with modifications of intracellular cAMP and calcium levels (Islam et al., 1995; Hattori, Moriwaki, & Hori, 1990). The dependence on receptor efficacy changes and protein synthesis may be why it takes a few minutes of stimulation before tDCS can have an offline affect on behavior. Nitsche and Paulus (2000) found that in motor cortex, a minimum of 3 min of anodal stimulation at 1 mA current was required to produce NMDA/GABA-mediated after-affects on motor evoked potentials. The minimum was 5 min at 0.6 mA. Given that 1.5 mA of current was used in this investigation, the expected period prior to the onset of synaptic effects may have been even shorter than 3 minutes. However, it is also possible that there is a ceiling effect as far as the speed with which such effects can be elicited, perhaps due to some sort of synaptic/cellular limitation.

Several studies have shown more persistent effects for cathodal stimulation; however, since little has been done with cathodal stimulation as far as parametric studies of offline effects, we will assume a similar onset time for synaptic effects of cathodal stimulation. To be clear, during the final two minutes of visual search, stimulation would be prompting both changes in membrane polarity and intracellular changes in receptor efficacy and protein synthesis, either or both of which could affect response times.

For the first 10 minutes of online CRA problem solution, participants would be experiencing both membrane potential effects and synaptic effects of stimulation, which will be referred to in this paper as online stimulation. Previous research suggests that post-stimulation (offline) effects tend to persist at least as long as the period of active stimulation (Nitsche & Paulus, 2001). The research of Nitsche and colleagues (2005), which showed that 9-13 minutes of stimulation could affect changes that last up to an hour in motor cortex, suggests that after stimulation ends, offline (intracellular) effects could have lingered for at least as long as it took participants to complete the rest of the CRA problem set.

In summary, direct current stimulation affects neuronal membrane potentials almost instantly and causes more lasting changes in receptor efficacy and protein synthesis after only a few minutes. It is unknown whether rapid effects in neuronal electrophysiology and less transient effects on neurochemistry differentially affect the behaviors of interest, specifically insight solution strategies and the encoding and/or recall of solutions, therefore those problems were not begun until participants had a chance to adjust to stimulation and until potential synaptic changes had begun to occur. Because active (online) stimulation ends in the middle of the CRA problem set, there was an opportunity to compare online and offline effects of stimulation on behaviors of interest.

2.6 Design

The study was a 3x2x2 mixed model design with stimulation type as a 3-level (anodal, sham, cathodal) within-subjects independent variable, stimulation order as a 2-level (anodal-sham-cathodal, cathodal-sham-anodal) between-subjects independent variable, and recall as a 2-level (session 1, session 2) between-subjects variable.

There were 5 main dependent variables of interest:

1) *insight solutions* (the mean number of problems solved with insight);

2) *insight percentage* (problems solved with insight as a percentage of total problems solved, “not sure” responses excluded);

3) *insight solution time* (the period between stimulus presentation and participant-indicated solution for problems solved with insight);

4) *error rate* (the percentage of responses that were wrong); and

4) *recall rate* (the number of problem solutions recalled).

Other dependent variables analyzed in order to aid interpretation included *analytic solutions, and analytic solution time*. The first two variables were assessed separately to account for the possibility that stimulation benefits problem solving regardless of whether the problem solver used insight or analytic strategies, in which case production of insight solutions would increase but the insight/noninsight ratio would remain the same.

In summary, this study was designed to investigate the effects of tDCS stimulation of rASTG on insight solutions of CRA problems and to investigate whether insight solutions were more easily recalled than noninsight solutions. The design of the study also enabled us to pursue some exploratory aims of adding to extant literature on the time course of effects of DCS stimulation.

2.7 Procedure

Participants completed 3 90-minute sessions in which they were given one of three types of direct current stimulation while they solved visual search and compound remote associates problems. They were consented when they appeared for the first stimulation session. At the beginning of the first session they were asked to fill out a form verifying that they met the exclusion criteria (Appendix C), as well as the Edinburgh Handedness inventory (Appendix E). After they are consented and filled out the forms, participants sat in front of a laptop computer with a modified keyboard (figure 6).

Figure 6. The modified keyboard

The experimenter said:

> *"You will be asked to complete two tasks, visual search and compound remote associates problems, both of which will be explained in a minute. When you respond to these tasks, you will be asked to press keys on different sides of the keyboard at the same time, always the same colors. Try to press them at the same time. If you are not pressing them at the same time, the program will tell you. Try to respond as soon as you have an answer, so it is best to keep your hands on the keyboard. Try to respond quickly, but be accurate. Do you have any questions?"*

> *"First we will begin with some practice problems, so you get used to the main task. Some of these problems are easy and some are very difficult. No one would be expected to solve all of the problems, so just do the best you can."*

> *"Three problem words will be presented on the screen. You must generate a solution that can form a compound word or phrase with each problem word. The solution word can precede or follow each problem word. For example, if you are given the words pine, crab and sauce, you are trying to generate the word apple, which will combine with those problem words to form pineapple, crabapple and applesauce. As soon as you feel you have the correct answer, press the two blue keys at the top of the keyboard at the same time. Immediately after you press the blue keys, say your answer out loud."*
>
> *"After you say the answer, you will be asked if you solved the problem using insight or not. This is an important part of the experiment. Insight is the sudden realization that you have the correct answer. You may have switched your train of thought just before you realized you had the answer. Insight is usually accompanied by an 'Aha!' feeling. If you solved the problem with insight, press the "INSIGHT" key. If you solved the problem without insight, press the "NO INSIGHT" key. Try to pick one or the other. If you are really not sure, press the "NOT SURE" key. After that, you will be asked to type the answer. Please try to type it correctly and then hit enter (which is the insight key). After a few more seconds, you'll be given another problem. Do you have any questions? Are you ready?" (*Subramanian et al., 2009).

If participants were still unclear as to the distinction between insight and analysis, it was emphasized that insight involves the solution coming without partial solutions. For example, a person can fail at a trial-and-error process and then just sit for a bit and still have a sudden insight. The suddenness of the insight refers less to time than to the fact that the person did not perceive progress toward an answer. But with insight the answer suddenly "pops in" and is obviously correct and is accompanied by the "Aha!" feeling. In such cases, the importance of this distinction was reemphasized, and participants were encouraged to hit the 'Not Sure' key only when they really could not determine which strategy they had used. Participants were also told they should take a little time to think about/answer the insight strategy question, which did not time out.

Participants were given 5 CRA problems to practice. All stimuli were delivered via E-prime 2.0 (Psychology Software Tools, Inc.) software. On the computer screen, participants saw a "Ready?" prompt, followed by a fixation cross for 1 second and then 3 problem words were presented on the screen. The three words were centered just above the fixation point, at the fixation point, and just below the fixation point. Each three-word problem stimulus was on the screen for a maximum of 30 s. Immediately after participants struck both keys at the same time to indicate a solution, a solution prompt ("Solution?") appeared on screen. Participants were given 3 s to say the solution. If no solution was produced within 3 s of the bimanual button press, the trial was counted as an error. After the participant responded orally, an insight prompt ("Insight?") appeared. Participants then indicated if they achieved solution with insight or without insight or if they are 'not sure.'

Preparation for tDCS involved measurement of the participant's head and placement of the two electrodes was accomplished with the extended international 10-20 electrode placement system. The active electrode was placed at T8, which is proximal to the area of interest (rASTG, Talairach coordinates 41, -6, -12, in Jung-Beeman et al., 2004) and is the primary electrode from which rASTG activity prior to insight was detected by EEG. The sponge-covered electrodes were secured directly against the scalp with straps that were wrapped around the head (figure 7, Appendix A).

After the electrodes were secured to the participant's head, but prior to receiving stimulation, participants attempted to solve a series of visual search trials for 5 minutes. Participants were told:

> *"To complete this task you will be searching the array of objects to see if there is a letter L. If you see the letter 'L' among the other objects with similar shapes but different orientations, press the two green keys labeled 'YES' on the outer part of the keyboard at the same time. If you do not see the letter 'L' among the other items, press the two red keys labeled 'NO' at the same time. Please respond as fast as you can. Between each array of objects, you will wait for a second while a fixation cross appears. Are you ready?"*

During visual search, participants were presented with different arrays of 8 objects. Among the objects, a pre-identified target item (the letter L) appeared about half the time (figure 3). The rest of the time there was a distractor item instead of the target item. The array was on the screen until the participant responded or 5000 ms had elapsed, at which point the next array was presented. Between visual search stimuli, there was a 500 ms interval in which the screen is blank, followed by a central fixation cross that appeared for 500 ms (as per Ellison et al., 2004). After participants were engaged in the visual search task for 5 min, it was briefly paused and direct current stimulation began.

Both the stimulation and reference electrode were wrapped in saline-soaked sponges and did not contact the scalp directly. Direct current was applied with an Eldith DC-Stimulator^{Plus} (Magstim), a device that has been approved by the United States Food and Drug Administration for investigational use (The Magstim Company Limited, 2008). The device was powered by rechargeable batteries and includes a microprocessor controlled unipolar and bipolar constant source for anodal and cathodal stimulation. Participants were randomized to receive either anodal (positive pole) stimulation or cathodal (negative pole) stimulation. On the second day all participants received sham stimulation. On the third day, participants received cathodal stimulation (if they received anodal stimulation on the first day), or anodal stimulation (if they received cathodal stimulation on the first day). Anodal stimulation was given at 1.5 mA of current for a total of 15 min. Cathodal stimulation was also be given at 1.5 mA of current for a total of 15 min (Nitsche et al., 2008). Sham stimulation was given at 1.5 mA of anodal current for 15 s (Gandiga, Hummel & Cohen, 2006). After participants received 5 min of stimulation or sham (during the second half of the visual search task), they were told:

> *"Now you will be asked to solve a series of problems like the ones you practiced before. Remember, as soon as you feel you have the correct answer, press the two blue keys at*

the top of the keyboard at the same time. Immediately after you press the blue keys, say your answer out loud… Any questions?"
"Remember to give some thought to how you solved it (insight or no insight) because this is an important part of the experiment."

After solving problems for 10 min, stimulation was slowly extinguished via an automatic pre-programmed process that most participants cannot detect (Gandiga, Hummel, & Cohen, 2006). The display on the Magstim Eldith Stimulator^{PLUS} device shows stimulation parameters, such as current, in real time (figure 2), but the display was hidden from participants. Participants continued to try to solve CRA problems until the set was finished, a process that usually lasted approximately 15 minutes. Solutions were recorded in real time by the E-Prime software, which also recorded the number of problems solved with insight and the number of problems solved without insight during each session. Solution times (time between problem presentation and indication that a solution had been reached via bimanual button press) were also recorded for each problem solved. After participants finished solving the CRA problems, they solved visual search problems, as before, for 10 min.

The following recall task was performed only during the first session (active stimulation, either anodal or cathodal) for 66% of the participants and only during the second session (sham) for 33% of the participants. Participants were randomly allocated to one of the two conditions. After the visual search task, some participants were told:

"Earlier, you tried to solve a series of word problems in which you had to find a word that formed a compound phrase with three other words. You succeeded at solving some and some remain unsolved. I want you to try to write down all the SOLUTIONS you came up with. Do not write down the words that were shown to you on the screen. Just type in the ones that you said."

Participants had an empty field into which they could type the solutions that they can recall. They had about 5 minutes to respond and were prompted to attempt to recall solutions for at least 3 minutes. This trial was an incidental memory task, because participants were not aware that they would have to remember the solutions. In subsequent CRA trials following a recall session, participants were told: *"You will NOT be asked again to recall the answers like you were before, so don't worry about trying to remember them. Just worry about solving the problems."*

In all 3 sessions participants were given another chance to solve the problems they could not solve the first time. They were told: "So these are the ones you got wrong a little bit ago. Please try them again and see if you can figure out a few more. Even if it is a bit frustrating, just try the best you can." E-prime referenced the database (into which the participant entered responses) to determine which CRA problems were not correctly solved and should be presented again in the second-chance condition. (The results of the post-incubation aspect of the experiment were part of another experiment and will not be commented upon here.)

After participants completed the "second-chance" trials, the tDCS apparatus was removed from their heads and they were compensated. After the third session, they were debriefed as to the nature of the experiment and asked if they had any questions.

2.8 Hypotheses

2.8.1 Preliminary analyses of assumptions

2.8.1.1 CRA practice effects: CRA problem solution has not been thought to benefit from learning effects (Kounios, personal communication, 2009). It was assumed that there would be no significant practice effects for solving CRA problems, but analyses comparing CRA solution times and overall CRA solution accuracy, both within-session and between-sessions, were planned to check this assumption.

2.8.1.2 Stimulation order effects: The offline effects of a single session of stimulation are thought to wash out in a relatively short amount of time. Estimates of single-session washout in the literature range from an amount of time equal to the period of stimulation (Nitsche & Paulus, 2000) to up to several hours (Reis et al., 2009). When stimulating temporal cortex, different investigators have spaced sessions 48 hours apart after 2 mA for 30 minutes (Boggio et al., 2009b) and up to 7 days after 1 mA for 20 minutes (Floel et al., 2008). The later study specified that the spacing was to avoid carryover effects but it was unclear whether the concern was about carryover effects of stimulation or the behavioral intervention. It has been suggested that for around 10 min of stimulation, a break of 1 h is sufficient (Fregni et al., 2005) and for stimulation sessions exceeding an hour, 48 h to a week has been suggested as an appropriate washout period (Nitsche et al., 2008). Based on previous studies, a 48-hour washout period seemed quite appropriate for 15 minutes of 1.5 mA stimulation. It was hypothesized that there would be no difference in dependent variables between post-anodal-stimulation sham post-cathodal-stimulation sham. Post-hoc analyses were planned to check that assumption.

2.8.1.3 Influence of recall session: Due to the variable placement of the recall assessment in either session 1 or session 2, preliminary analyses were planned on dependent variables of interest during session 2 (sham), with recall during session 1 as the dichotomous independent variable.

2.8.2 Direct current stimulation's effects on CRA problem solving

Recent investigations of electrophysiological activity during insight solutions of verbal problems demonstrated significant increases in right temporal lobe activity after problem presentation and increased gamma-band activity immediately prior to insight. Functional magnetic resonance imaging localized that activity to the rASTG. That finding, combined with data showing a correlation between rASTG activity immediately after problem presentation and subsequent solution with insight, suggests a positive correlation between rASTG activity and insight solutions of verbal problems (Jung-Beeman, 2004). This research sought to clarify the role of the rASTG in achieving insight solutions of compound remote associates problems. Rather than using EEG or fMRI to replicate previous results demonstrating that rASTG activity predicts insight solution of CRA problems, this investigation used direct current stimulation to alter neuronal excitability in the rASTG while participants attempted to solve CRA problems. The goal was to explore the possibility that activity in the rASTG contributes directly to the adoption and implementation of insight solution strategies for verbal problems.

During solution of CRA problems, participants had a 10-min period during which they solved CRA problems while undergoing stimulation, followed by a 15-min period after stimulation, during which there were presumed to be lingering offline effects of stimulation. Because it is possible that the effects of stimulation on CRA problem solving performance depend on whether stimulation was online or offline, we wanted to compare the effect of stimulation on CRA solution during and after stimulation. These comparisons also had the potential of adding to the sparse literature about effects of online versus offline stimulation. Due to the paucity of information about how these effects might differ, we assumed that the behavioral effects of stimulation would diminish over time.

2.8.2.1 Hypothesis 1A: Anodal stimulation will enhance insight: Because excitatory anodal stimulation of temporal cortical areas with direct current has been shown to enhance cognition (Boggio et al., 2009a; Floel et al., 2008), and greater activity in rASTG is associated with insight, it was hypothesized that compared to sham or cathodal stimulation, anodal tDCS applied to rASTG during solution of CRA problems would enhance the use of insight in solving CRA problems. There are four ways that we tried to describe the anticipated effect:

1. Anodal stimulation will cause CRA problem solvers to use insight more frequently to solve problems when compared to sham and cathodal stimulation.
2. Anodal stimulation will increase the effectiveness of insight strategy application (more insight solutions) compared to sham and cathodal stimulation.
3. Anodal stimulation will increase the speed of insight solutions compared to sham and cathodal stimulation.
4. Anodal stimulation will reduce the percentage of incorrect insight responses compared to sham and cathodal stimulation.

2.8.2.2 Hypothesis 1B: Cathodal stimulation will impede insight: Based on previous findings that cathodal stimulation hyperpolarizes neuronal membranes and reduces cortical activity, it was also hypothesized that cathodal direct current stimulation of rASTG during verbal problem solving would impair the use of insight to solve CRA problems. There were four ways that we tried to describe the anticipated effect:

1. Cathodal stimulation will cause CRA problem solvers to use insight less frequently to solve problems when compared to sham and anodal stimulation.
2. Cathodal stimulation will decrease the effectiveness of insight strategy application (more insight solutions) compared to sham and anodal stimulation.
3. Cathodal stimulation will decrease the speed of insight solutions compared to sham and anodal stimulation.
4. Cathodal stimulation will increase the number or incorrect insight responses compared to sham and anodal stimulation.

2.8.3 The recall of CRA solutions

2.8.3.1 Insight and recall: Several studies have suggested that insight improves recall. While some have found that using insight to solve the problem makes the problem more memorable (Auble, Franks & Soraci, 1979; Wills, Soraci, Chechile and Taylor, 2000), others have found that insight makes the solution more memorable (McCabe, unpublished). This study further explored the possibility that insight improved recall of declarative information by testing participants' free recall of solutions to CRA problems after a brief incubation period in which participants solved simple visual search problems.

2.8.3.2 Hypothesis 2A: Based on previous findings that insight solution strategies improve recall of declarative information, it was hypothesized that participants would recall solutions achieved via insight more often than solutions in which they used analytic or search processes.

2.8.3.3 Does stimulation affect recall? It is possible that stimulation may affect the degree to which solution information is encoded or retrieved. In a recent study (Kirov, Weiss, Siebner, Born & Marshall, 2009), investigators demonstrated an effect of slow oscillatory DCS (in which current ramps up and down at 0.75 Hz) on free recall of verbal word lists. There have also been studies demonstrating DCS effects that have improved language learning (Floel et al., 2008) via stimulation of Wernicke's area, so it was reasonable to suspect that stimulation may have facilitated recall. It is likely that cathodal stimulation applied to the right ASTG will also affect other areas, perhaps extending to the contralateral homolog of Wernicke's area and even to hippocampal regions. It was also speculated that activation of Wernicke's area could be increased due to a reduction of contralateral inhibition, which could increase encoding/learning. Alternatively, right-sided anodal activation could affect the strength of coarse semantic representations in temporal cortex (Bowden & Jung-Beeman, 2003b; Beeman & Bowden, 2000), which could be more easily referenced during recall and lead to a more rapid retrieval of problem data for which solutions are not immediately recalled.

2.8.3.4 Hypothesis 2B: After weighing the possibilities described above, it was hypothesized that cathodal stimulation would increase recall of solutions more than sham stimulation or anodal stimulation due to its reduction of contralateral inhibition.

3. RESULTS

3.1 Overview

The preliminary analyses revealed that during the course of three sessions of CRA problem solving, participants changed the proportion of insight they used to solve CRA problems, using progressively more analysis. The rate of response errors decreased significantly between sessions. Problem solution rates and times were not significantly different between sessions. There were no significant between-groups differences. There were no between-sessions effects of recall or between-sessions effects of stimulation.

Hypothesis 1A stated that transcranial direct current simulation of rASTG with anodal stimulation would facilitate insightful solution of compound remote associates problems. That prediction was partially confirmed by the results reported here. Anodal stimulation was associated with faster insight solutions and an increase in the percentage of problems solved with insight.

Hypothesis 1B stated that cathodal direct current stimulation would interfere with insight processes. Hypothesis 1B was also supported. Cathodal stimulation did not significantly alter the proportion of problems solved with insight; however, it was associated with slower insight solution speeds and more erroneous insight responses.

Hypothesis 2A stated that insight solution strategy would provide an advantage for recall of solutions. There was no evidence to support that prediction.

Hypothesis 2B stated that stimulation would affect the recall of problem solutions. There was no evidence to support that prediction.

3.2 Participants

A total of 28 participants were recruited to receive three different types of transcranial direct current stimulation while solving CRA problems during three separate 80-min sessions. One participant discontinued at the beginning of the second session, so that participant's data is not included in any of the analyses. Three participants had no solution strategy data collected during session 1 due to a software malfunction. Those participants were only included in analyses that did not assess solution strategy. All analyses were performed both with and without them, and there were no qualitative differences in the data based on their inclusion or exclusion. One participant was excluded from all analyses due to never solving problems with insight during some sessions, a response style that was more than 2 standard deviations below the population mean for insight use. Participants were excluded from analyses if they were more than 2 standard deviations from the mean in either direction.

The final N rendered us slightly underpowered for some analyses by traditional measures of behavioral experimentation. However, although effect sizes in behavioral studies using tDCS are typically modest (Coslett, 2009), they are often quite consistent across participants. Consequently, many studies using tDCS have achieved statistically significant findings despite being statistically "underpowered."

Thirteen participants were randomized to receive anodal stimulation on the first session, and 14 participants received cathodal stimulation on the first session. A MANOVA showed no mean differences in age, education or gender, $F(26)=.199$, $p=.896$, between the two groups.

Overall, participants solved 39.70% (SD=10.82%) of the CRA problems. They had a mean problem solving time of 9.81 s (SD=2.02 s), and they used insight 63.09% (SD=19.39%) of the time.

Based on self-report, there were 7 Asian participants (25%), 7 African-American or Black participants (25%), 10 Caucasian or White participants (35.7%), and 4 multi-racial participants (14.2%). There were 13 males (46.4%) and 15 females (53.4%). The participant excluded from all analyses due to discontinuation was female.

3.3 Preliminary Analyses

3.3.1 CRA practice effects

Preliminary analyses were conducted to investigate possible practice effects on CRA problem solution between sessions and the degree to which solution time, solution rate (solutions/problem), insight percentage (insight solutions/total solutions), and/or error rate (responses – solutions) changed across sessions.

The design of this experiment was a 3x2 mixed-model design with a 3-level within-subjects variable (stimulation type: anode, cathode, sham) and a 2-level between-subjects variable (stimulation order: anode-sham-cathode, cathode-sham-anode), rather than a 6-level between-subjects variable. Stimulation order was not completely balanced in order to reduce the number of levels in the between-subjects “stimulation order” variable from 6 levels to 2 levels, which increased power to detect an effect.

A weakness in this design is that the second session is always sham stimulation. Therefore, when both types of stimulation altered a variable in the same direction compared to sham, such as by reducing solution percentage, it was difficult to disentangle the effects of time (session) from the general effects of stimulation. An alternative method to explore the possibility of practice effects on the solution of CRA problems was to compare the first session to the third session.

A MANOVA was performed with solution time, solution rate, insight percentage, and commission error rates as dependent variables and session order (anode first vs. cathode first) as an independent variable, (F=5.075, p=.002). Although there were no differences in participants' solution rate, or overall solution speed between the first and third session, there were significant differences between sessions with regard to insight percentage and error rates**.**

Table 3: Preliminary Analyses

(N=26, #22 excluded)	Session 1	Session 3	Mean Diff	F	P
Solution Rate	39.02%	38.87%	-0.17%	.747	.392
Solution Time	10.23 s	9.67 s	-0.56 s	.002	.963
Insight %	74.89%	59.76%	-15.13%	7.63	.008
Error Rate	24.82%	13.24%	-11.58	7.739	.008

Because error rates and insight percentages changed between sessions, stimulation order (anodal-first, cathodal-first) was used as a covariate in all analyses comparing stimulation effects.

3.3.2 Stimulation washout effects and group differences

There was a mean of 7.7 days (SD = 7.6 days) between the first and second session and a mean of 8.65 days (SD = 8.59 days) between the second and third session. Such long washout periods make lingering effects of stimulation highly unlikely (Nitsche & Paulus, 2001). In order to test for lingering effects of stimulation from session 1 on performance during session 2, and to explore possible group differences in problem solving performance, a MANOVA was conducted with stimulation order as the independent variable and session-2 problem solving rate, error rate, solution time, and insight percentage as dependent variables. There were no significant effects of stimulation order on problem solving rate, error rate, solution time or insight percentage during session 2 (sham), F(26)=1.142, p=.386. The same MANOVA was performed with all combinations of outliers excluded prior to subsequent statistical analyses and there were no significant group differences in sham CRA problem solving performance.

3.3.3 Recall condition effects

Because the recall condition was assessed once per participant, either in session 1 (66.67%) or in session 2 (33.3%), a MANOVA was conducted to see if having been in the recall condition affected subsequent performance on CRA problems. It is possible that participants tried to remember solutions (despite having been instructed that they would not need to recall them again) and that attempting to encode the solutions could have altered subsequent CRA solution strategies and efficiency. All participants had recall assessed before they reached session 3, and there were obviously no effects of recall on session 1 performance, because it was an incidental recall task. Therefore, dependent variables were problem solving rate (accuracy), error rate, solution time, and insight percentage. The dichotomous independent variable was session 1 recall (yes/no). There were no effects of recall on any of the variables of interest during session 2 CRA problem solving performance: $F(26)=1.18$, $p=.368$.

3.4 The effect of tDCS on insight strategies during CRA problem solving

3.4.1 The use of insight versus analysis

To test the hypotheses that anodal stimulation led to more frequent successful use of insight to solve CRA problems and cathodal stimulation decreased successful use of insight strategies, a repeated-measures ANOVA comparing participants' insight percentages during anodal (70.1%), cathodal (65.1%) and sham stimulation (61.8%) was conducted. There was a significant main effect of stimulation type on CRA solution strategy, as indicated by the percentage of problems solved with insight compared to analysis, $F(22)=5.178$, $p=.033$. (Not sure responses were excluded.) When session order was used as a covariate, including sham, the main effect of stimulation was again significant, F(22)=8.222, p=.001. A subsequent repeated-measures ANOVA, with stimulation order as a covariate, showed that compared to sham (61.8%), participants who received anodal stimulation (70.1%) were significantly more likely to use insight to solve CRA problems; F(22)=4.424, p=.047. These findings support hypothesis 1A: compared to sham, anodal stimulation of rASTG activity was associated with a tendency to use insight strategies successfully. The findings do not support hypothesis 1B, which predicted that during cathodal stimulation participants would be less likely to use insight. (In fact, insight percentage during cathodal stimulation (65.1%) was slightly higher than sham (61.8%), although the difference was not significant; t(22)=-.830, p=.415. Cathodal stimulation insight percentage was not significantly lower than anodal stimulation insight percentage; t(22)=.939, p=.358.

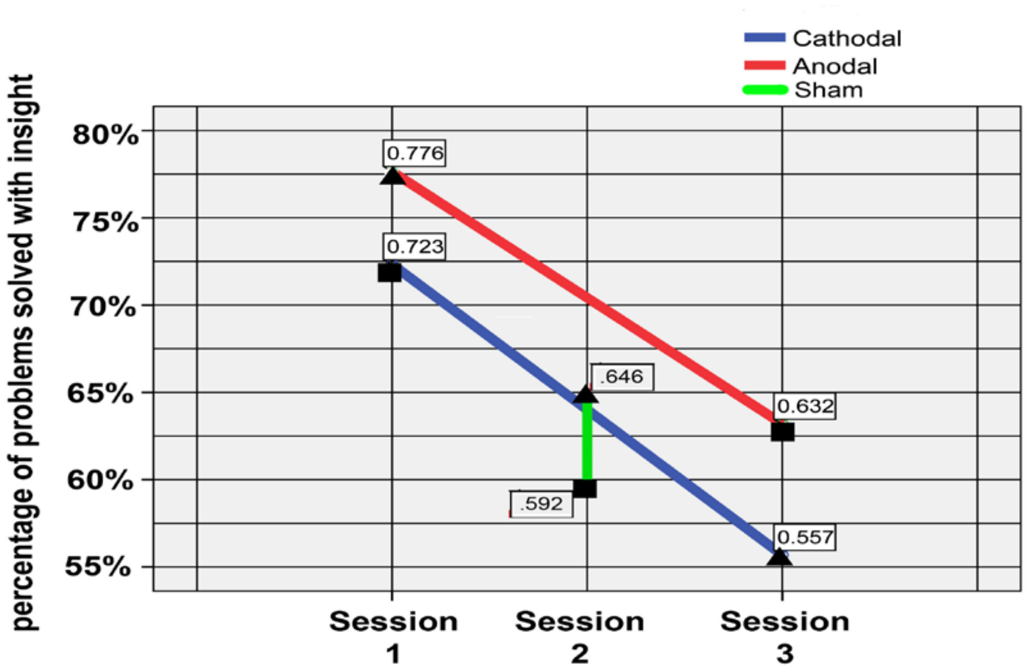


Figure 8: Percentage of problems solved with insight across sessions. Triangles identify session means for the group allocated to receive anodal stimulation first. Squares identify session means for the group allocated to receive cathodal stimulation first.

3.4.2 Solution rates

Overall, anodal stimulation was associated with a reduction in CRA solution rate. Participants receiving anodal stimulation solved 38.51% of the CRA problems while those receiving sham stimulation solved 42.13%, which was a marginally significant difference when stimulation order was included as a covariate, F(22)=3.908, p=.061.

3.4.2.1 Insight solutions: Hypothesis 1A also predicted that anodal stimulation would increase the raw number of insight solutions of CRA problems. This prediction was not supported by the data. A repeated-measures ANOVA, F(22)=.032, p=.859, found no differences in mean insight solutions between anodal (15.3 solutions), cathodal (14.86 solutions) and sham stimulation (15.09 solutions). The prediction of hypothesis 1B that cathodal stimulation would decrease the number of insight solutions was also not supported.

3.4.2.2 Analysis solutions: Given that insight solution percentages increased with anodal stimulation relative to sham, and yet the total number of insight solutions remained unchanged, it was assumed that there must have been a reduction in the number of analysis

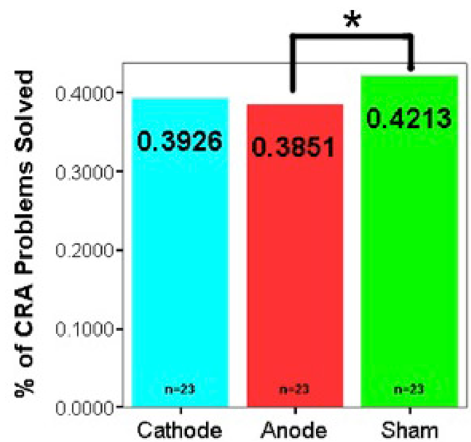


Figure 9: CRA solution rate

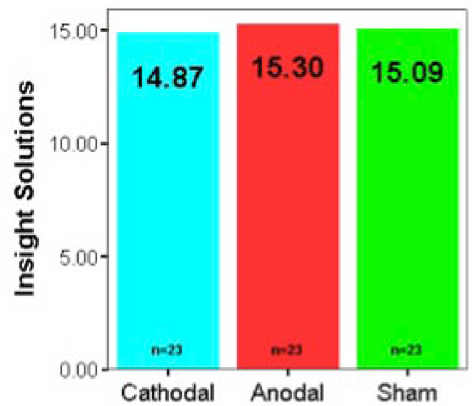


Figure 10: Insight Solutions

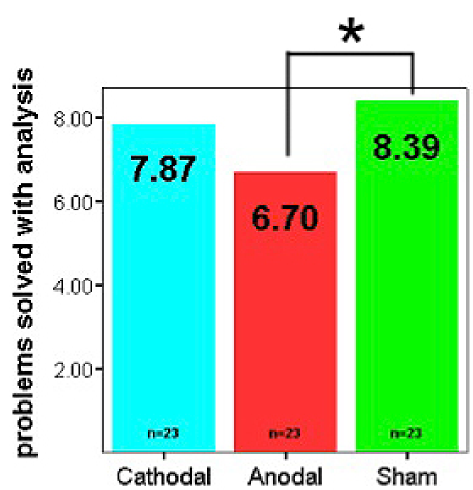


Figure 11: Analysis Solutions

solutions to have increased the relative percentage of insight solutions. A repeated-measures ANOVA, with stimulation order as a covariate, indicated a difference in mean analytic solutions between anodal stimulation (6.70 analytic solutions) and sham stimulation (8.78 analytic solutions), F(22)=5.787, p=.025. There were no significant differences between anodal stimulation and cathodal stimulation for analytic solutions, nor was there a significant difference between cathodal stimulation and sham.

3.4.3 Insight solution speed

Hypothesis 1A correctly predicted that anodal stimulation would be associated with faster solutions of CRA problems using insight. A repeated-measures ANOVA, with stimulation order as a covariate and insight solution times log transformed, was performed to compare mean insight solution times during anodal stimulation (8.57 s), cathodal stimulation (9.35 s) and sham stimulation (9.61 s), F(20)=4.799, p=.014. Two subsequent planned repeated-measures ANOVAs, with stimulation order as a covariate and insight solution times log transformed, found that anodal stimulation was associated with significantly faster insight solution speeds compared to sham stimulation; F(20)=5.461, p=.031, and compared to cathodal stimulation; F(20)=7.58, p=.013. Hypothesis 1B, which stated that insight problems would be solved more slowly during cathodal stimulation, was not supported. Interestingly, when the effects of active online stimulation are examined in isolation, there was a significant difference between anodal stimulation and cathodal stimulation, F(19)=7.856, p=.012; with both active stimulations

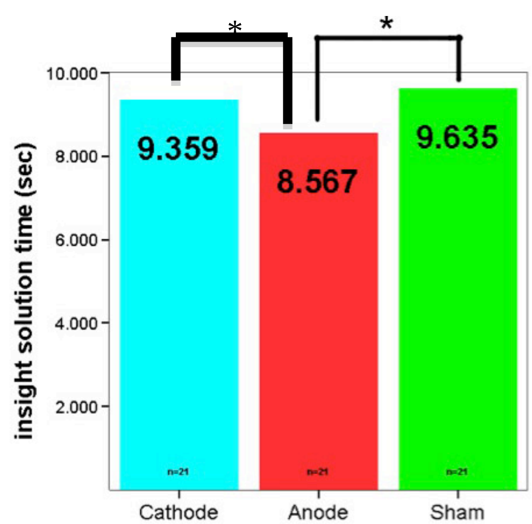


Figure 12: Insight Solution Times

altering insight speeds in opposite directions compared to sham (Appendix B).

3.4.4 Errors

3.4.4.1 Insight error rates: Based on the assumption that the rASTG is actively involved in integrating semantic activations to achieve an insightful solution to a CRA problem, it was predicted (hypothesis 1A) that anodal stimulation would be associated with more accurate insight. So, participants who received anodal stimulation should have had fewer occasions when they indicated an insight and had a wrong answer (response error). A repeated-measures ANOVA (with session order as a covariate to control for the tendency of participants to make fewer errors as they complete more sessions) was performed to compare mean insight error percentages associated with anodal stimulation (7.71%), cathodal stimulation (10.19%) and sham stimulation (5.52%). According to the RM-ANOVA, F(19)=3.754, p=.045, there was a significant difference. Follow-up RM-ANOVAs were conducted to compare anodal stimulation to sham, F(19)=.109, p=.744, and anodal stimulation to cathodal stimulation, F(19)=-0.876, p=.392. The analyses showed no significant differences, suggesting no effect of anodal stimulation on insight error rates overall. (See Appendix B for a breakdown of significant online effects of anodal stimulation on error rates.)

It was also predicted (hypothesis 1B) that cathodal stimulation would be associated with significantly more insight errors than sham stimulation or anodal stimulation. A repeated-measures ANOVA was conducted to compare insight errors in the cathodal condition to the sham condition, with stimulation order as a

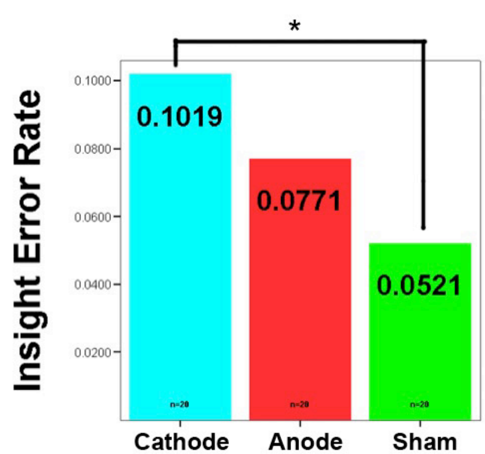


Figure 13: Insight Error rate

covariate. The analysis demonstrated that cathodal stimulation was associated with significantly more erroneous insight responses, F(19)=4.954, p=.039.

3.4.4.2 Changing error rates between sessions: A more general exploration of error rates was undertaken in order to determine if stimulation was having effects on analysis solutions as well. A repeated-measures ANOVA, with stimulation order as a covariate, demonstrated a significant difference in mean error rates among anodal stimulation (17.86%), cathodal stimulation (14.5%) and sham (12.71%), F(19)=6.989, p=.003. Follow-up repeated-measures ANOVAs (with session order as a covariate) found that anodal stimulation was associated with more erroneous responses overall compared to sham stimulation, F(19)=6.715, p=.018. There were also significantly more errors associated with anodal stimulation compared to cathodal stimulation, F(19)=10.809, p=.004. The difference between cathode and sham error rates was not significant, F(19)=2.235, p=.152.

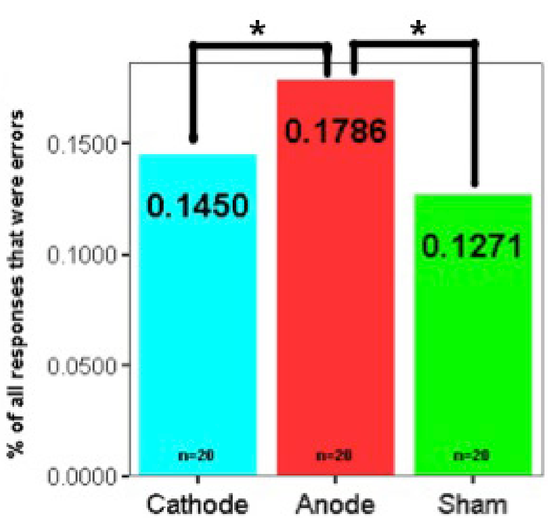


Figure 14: Error rates across stimulation

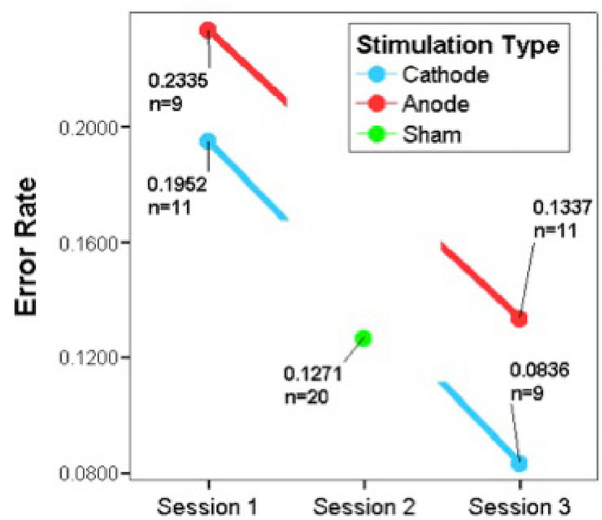


Figure 15: Changing error rates between sessions

3.4.4.3 Analysis Error Rates: Given the large effect of anodal stimulation on overall error rates and its negligible effect on insight error rates, it seemed reasonable to assume that anodal stimulation significantly interfered with analysis error rates. Unfortunately, because it was not unusual for participants to have only a few analysis responses, the error rates were quite variable and a repeated-measures ANOVA examining error rates that can be as high as 66% in some cases with just a few responses should be interpreted with caution. However, a repeated-measures ANOVA, with stimulation order as a covariate, found a marginally significant effect of stimulation type on analysis error rate; F(23)=2.752, p=.075. Follow-up repeated-measures ANOVAs with stimulation order as a covariate, comparing anodal stimulation to cathodal stimulation found no significant differences in mean analysis error rates; F(23)=2.965, p=.100. There was a significant difference between anodal stimulation and sham; F(23)=6.223, p=.021.

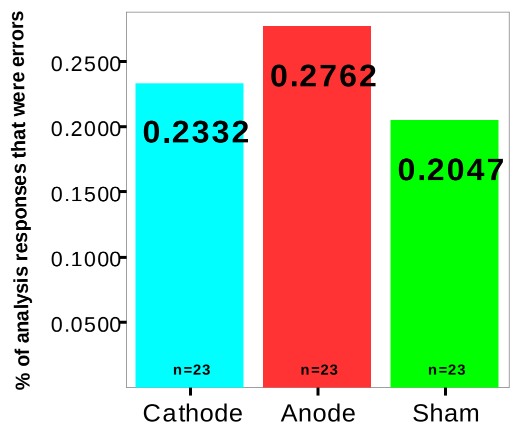


Figure 16: Analysis Error rates

3.5 Does insight benefit recall?

3.5.1 Does insight affect recall?

Recall was incidental and assessed only once per participant. Participants recalled 19.4% of correct responses. Participants recalled an average of 4.72 (SD = 2.45) correct solutions from an average of 24.42 (SD = 5.21) problems solved.

A paired-samples T-test was conducted to see if the insight percentage for participants' recalls was significantly different than it was for their solutions. Three participants who had recall totals (X=4.72, SD=2.45) or insight solution percentages (X=68.1%, SD=22.3%) that were more than two standard deviations from the mean were excluded. The percentage of problems solved with insight (68.6% after exclusions) was not significantly different from the insight percentage for solutions recalled (62.4%); t(23)=-.648, p=.532).

Although this analysis was underpowered to detect an effect, given that the percentage of problems solved with insight (68.6%) was higher than the percentage of recalled solutions that had been achieved with insight (62.4%), there did not seem to be a significant benefit to recall from the insight solution strategy in this exploration.

3.5.2 Stimulation and solution recall

Did cathodal stimulation increase recall? Participants recalled a mean of 5.10 (SD=3.11) solutions after cathodal stimulation, 4.86 (SD=2.12) solutions after anodal stimulation and 4.29 (SD=2.39) solutions after sham stimulation. An ANOVA detected no effect of stimulation condition on solutions recalled, F(23)=.225, p=.800, though the analysis was grossly underpowered at an estimated power of only .081.

Another way to examine recall and stimulation is to account for variable solution rates by dividing raw recall numbers by total solutions achieved during the recall session. An ANOVA was conducted with stimulation condition as the independent variable and recall accuracy as the dependent variable. Mean recall accuracy for anodal stimulation was 18.8% (SD=8.2%), cathodal stimulation was 21.7% (SD=7.9%), and sham stimulation was 20.2% (SD=6.8%). There was still no observed effect of stimulation type on recall accuracy, F(23)=1.209, p=.323.

3.6 Results Summary

Anodal stimulation was associated with enhanced use of insight for CRA problem solving. It significantly increased the proportion of problems solved by insight (by interfering with analytical solution production rather than increasing the number of insight solutions). Participants who received anodal stimulation also solved problems faster with insight than did participants who received cathodal stimulation or sham stimulation. Participants in the anodal stimulation condition identified fewer errors as insight than participants in the sham condition. Finally, participants who received anodal stimulation produced significantly more errors when solving problems with analysis than did participants who received sham stimulation.

The prediction that cathodal stimulation would impede the insight solution process was supported to a lesser extent. Cathodal stimulation did not significantly affect the proportion of problems solved with insight compared to sham, although there was an increase in insight solution percentage. Cathodal stimulation was associated with slower solution of problems with insight compared to anodal stimulation and it was associated with twice as many errors on insight problems as anodal stimulation.

There were no significant facilitating effects of solution strategy on solution recall. There was also no significant effect of stimulation on solution recall. This was an exploratory aim of the investigation and, because it was underpowered, only a very large effect would have been detected.

4. GENERAL DISCUSSION

4.1 Mechanisms of Insight

4.1.1 ASTG in language processing and insight

The dominant role of the ASTG in language processing is presumed to be semantic integration: the detection, elaboration and refinement of higher order semantic relations. The right ASTG integrates semantic associations that are weak and coarse, while left ASTG integrates semantic associations that are stronger and fine (typically dominant) (Jung-Beeman, 2005).

During CRA problem solving, the ASTG has been shown to be active bilaterally (Jung-Beeman et al., 2005). Analytic solution strategies are thought to rely primarily on fine semantic associations stored in the left hemisphere, while insight solution strategies access the right hemisphere's coarse nondominant semantic associations (Jung-Beeman, 2005).

Structuring or restructuring the problem space is a vital step in the insight solution process according to the theories on which this research is based (Kaplan & Simon, 1990; Ohlsson, 1992; Knoblich, Ohlsson, Haider, & Rhenius, 1999; Jung-Beeman et al., 2004). At some point prior to insight, the solver must structure or restructure the problem space by shifting solution strategy so that meta-cognitive attentional resources are applied to non-dominant semantic associations represented in the right hemisphere rather than the dominant semantic associations

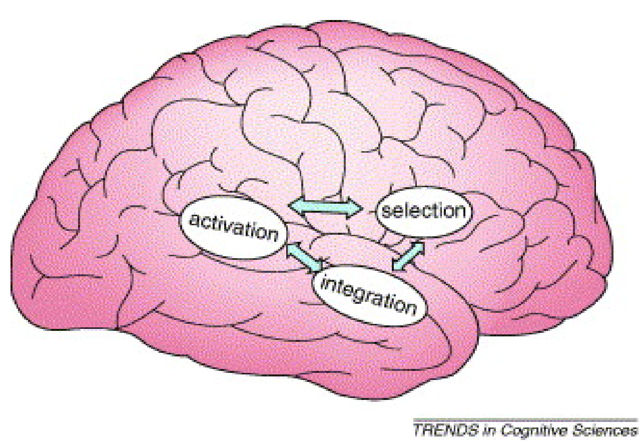


Figure 17: Natural language comprehension in the right hemisphere

represented in the left hemisphere (Kounios et al., 2006; Jung-Beeman, 2005). ASTG is active bilaterally upon problem presentation, presumably facilitating the integration of semantic fields in order to provide potential solutions, and a spike in gamma frequency activity in rASTG immediately precedes indication of insight solution.

4.1.2 The role of the right ASTG

There are several possible explanations for the rASTG's role in insight processes. The working assumption on which this research was based was that the burst of activity is the insight, i.e. the point at which the right ASTG integrates the disparate semantic associations and a solution becomes apparent. That assumption is based on the temporal relationship between rASTG activity and solution indication, and the fact that gamma frequency activity in temporal cortex is associated with activation of semantic representations (Pulvermuller, 2001). The goal of this investigation was to explore whether insight solution processes could be altered by modulation of right ASTG activity. When discussing what the findings reported here suggest about insight mechanisms, we must consider that the rASTG could be involved in one (or more) of the following roles:

1) rASTG activity may determine the speed, efficiency, and/or success of integration of coarse semantic associations and their conscious realization. This possibility essentially assumes that insight processes are driven by the rASTG and that increasing activity there will increase the speed, accuracy or success rate of insight.

2) rASTG activity may reflect solution progress, or the solver's potential to reach a solution, and contribute to restructuring via bottom-up signaling to anterior areas;

3) rASTG may act as an alert mechanism to indicate a solution has already been reached (without direct contribution to achieving the solution); and/or

4) rASTG may have no special role in insight and therefore altering underlying activity would not affect insight processes to the exclusion of analytic processes.

4.2 Interpreting the Effects of Direct Current Stimulation

In attempting to elucidate the role of rASTG in insight processes, interpreting the effects of stimulation is complicated by both the inter-relationship between insight and analytic processes during CRA solution and the interhemispheric effects of stimulation caused by contralateral reciprocal inhibition.

4.2.1 Interdependence of insight and analysis

If insight and analytic functions were completely lateralized and discreet, unilateral stimulation might affect implementation of one strategy without affecting the other. However, very few cognitive processes operate in such isolation, certainly not any as complex as verbal problem solving. It is highly unlikely that CRA problems are ever solved in a completely lateralized fashion; i.e., with only analytic or insight mechanisms. While the balance of anterior resources may shift from one hemisphere to the other, depending on which solution strategy is dominant, analytic and insight solution mechanisms remain intertwined.

Not only do both strategies rely on many of the same core abilities, such as working memory, general problem solving ability, and vocabulary (Ash & Wiley, 2006; Fleck, 2008; Gilhooly & Murphy, 2005), but the ability of the problem solver to employ insight may depend on previous application of analytic strategies to the same problem. A potentially significant influence on restructuring is the degree to which the problem solver experiences fixation or impasse, due to distraction by incorrect but dominant semantic associations. An ineffective focus on non-pertinent information that leads the problem solver away from a solution is thought to contribute to restructuring processes (Ohlsson, 1992; Seifert, Meyer, Davidson, Patalano, &

Yaniv, 1995), and CRA problems can mislead solvers because solution compounds often do not rely on the dominant meanings of the problem words. Failure to progress toward solution can be sufficient to trigger restructuring and insight (Chronicle, Ormerod, & MacGregor, 2001; Fleck & Weisberg, 2004), so impasse is not required for insight/restructuring. However, impasse does often precede insight and may contribute to restructuring (Metcalfe & Wiebe, 1987; Ohlsson, 1992).

Also, it is not presently known if restructuring solution strategies when attempting to solve CRA problems occurs once or multiple times. It is possible that switching back and forth between analytic and insight strategies is accomplished via anterior meta-cognitive attentional resources that are attracted by bottom-up signaling based on solution progress in either hemisphere.

Because of the interdependence of these processes, it can be difficult to determine if stimulation is affecting a strategy either directly and/or by enhancing or interfering with the other strategy.

4.2.2 Hemispheric rivalry

In addition to the interdependence of insight and analysis, brain interconnectivity further complicates attempts to understand the effects of “unilateral” stimulation. Because the hemispheres of the brain are engaged in constant inhibition of one another, anodal stimulation of the rASTG likely increases interhemispheric inhibition (figure 18); which essentially tips the scales against contralateral homologous areas in the left temporal cortex by increasing hemispheric rivalry (Kinsbourne, 1977). The opposite effect is presumed to be true for cathodal stimulation (figure 19), which should disinhibit the contralateral homologous area (left ASTG). Because of interhemispheric inhibition, when explaining possible effects of stimulation, one must consider that direct current stimulation of rASTG presumably affected both insight and analytic processes by differentially altering the semantic integration process in bilateral ASTG.

Although neither analytic nor insight processes are effected in isolation, hemisphere-specific effects of stimulation did seem to preferentially perturb specific strategies. Although stimulation may have modulated neural activity in other areas, due to current shunting and post-synaptic effects, for the purposes of this discussion, speculation about the effects of stimulation will generally be limited to temporal cortical areas, usually the right ASTG target area beneath the active electrode, and the left ASTG, which is modified by rASTG activity via contralateral inhibitory connections.

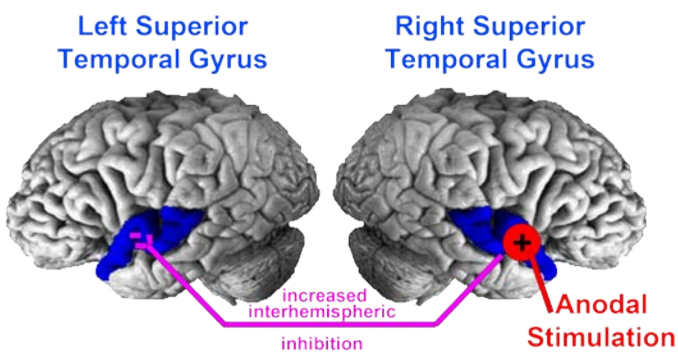


Figure 18: Anodal stimulation of right ASTG

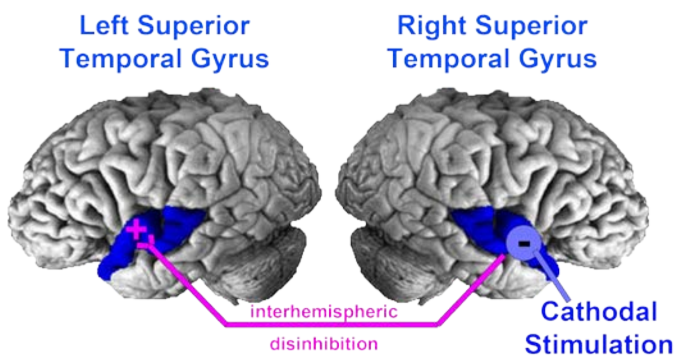


Figure 19: Cathodal stimulation of right ASTG

4.3 Interference with analysis

Anodal stimulation (compared to sham) of rASTG was associated with a tendency to solve a greater proportion of problems with insight, which fits the working model of verbal insight investigated here. However, this finding was a bit misleading because anodal stimulation was not associated with a significant increase in the number of insight solutions produced; rather, participants solved fewer problems using analysis, which elevated the insight percentage by reducing the denominator. Thus, although some aspects of insight solution processes were enhanced by anodal stimulation, the effects on insight percentage seem primarily due to interference with analytic processes.

4.3.1 Interhemispheric rivalry effects on analysis?

Anodal stimulation of right ASTG may have interfered with analytic (search) solutions of CRA problems via the enhancement of interhemispheric inhibition (figure 18). The increased inhibition of the left ASTG could have interfered with integration of fine semantic associations (Jung-Beeman, 2005), which could have allowed for fewer candidate solutions to be considered (Bowden, Jung-Beeman, Fleck & Kounios, 2005).

One might argue that if hemispheric rivalry was, in fact, the dominant mechanism by which stimulation affected analytic strategies, cathodal stimulation of rASTG should have disinhibited the contralateral area (figure 19) and led to more successful use of analytic strategies. That did not happen. In fact, cathodal stimulation also reduced the number of analytic solutions, although the difference (compared to sham) was not significant. The fact that left hemisphere disinhibition via right hemisphere cathodal stimulation did not increase analytic/search success could be explained by the possibility that left temporal semantic integration activity is not the limiting factor in producing analytic solutions to CRA problems; there could be a bottleneck elsewhere in the network. An alternate explanation is that such processes already operate at peak capacity and further disinhibition does not increase their speed or accuracy in a meaningful way with regard to analytic solution production. A third potential explanation is that disinhibition of left ASTG contributed to increased elaboration and detection of fine semantic association fields. Consequently, more readily detected associations may have been so salient they were difficult for the problem solver to ignore, which increased blocking and impasse and which could have produced additional timeouts and errors on problems that were being approached with predominantly analytic strategies, thus contributing to a slight decline in production rather than an increase.

4.3.2 Potential mechanisms by which anodal stimulation of rASTG affects analysis

Although the degree to which participants reach impasse or fail to progress towards a solution may be a main predictor of restructuring, it is also possible that activity in anterior attentional areas can be altered by bottom-up signaling from right and left temporal areas involved in semantic processing. Analytic and insight processes are interdependent in many respects; however, the success with which either right or left ASTG attract finite anterior attentional resources could be reflected as a loss of resources in the other hemisphere that reduces the effectiveness of the strategy mediated therein. Thus if a role of rASTG during insight is to recruit more meta-cognitive attention as solution progress is achieved, anodal stimulation may have facilitated that process. In effect, this would have altered the balance of activity such that anterior attentional mechanisms (possibly including the anterior cingulate cortex) were increasingly recruited, which could also have led to the increased use of other frontal resources such as the prefrontal cortex, which is thought to inhibit incorrect solution candidates (Kandhadai & Federmeier, 2010). The increased recruitment of frontal resources may have led to the parsing of more solution candidates in the right hemisphere compared to the left hemisphere (Kounios et al., 2006), which may have interfered with analytic processes because fewer frontal resources were devoted to left hemisphere-mediated analytic processes. If anodal stimulation of rASTG caused inappropriate or precipitous restructuring via recruitment of frontal resources away from left hemisphere driven analytic strategies, one might expect fewer analysis solutions, which is what happened.

Further support for the argument that anodal stimulation of rASTG could increase anterior resource recruitment comes from recent findings regarding intuition and immediate insight solutions. Stimulation may have increased intuition that a solution was obtainable. Recent research demonstrated that participants can intuit whether a CRA problem is solvable even when they do not know the solution (Bolte & Goschke, 2005), so there is some conscious access to solution progress or the potential to reach solution, even if the details of the process remain inaccessible to meta-analysis. Although that research did not disentangle insight from analytic problem solving processes, a defining aspect of intuition is that it is a nonconscious process (Dane & Pratt, 2009)—people do not know why they “know.” It is possible that rASTG anodal stimulation acted to increase this sense of a solution, or intuition. Cranford (2010) posited such intuition as a potential reason why participants described many rapidly solved problems as having been solved with insight—essentially their intuitions were verified, which yielded an affective response. Using fMRI, he found rASTG to be more active prior to the immediate solution of CRA problems with insight (as opposed to delayed insight solutions and analysis solutions). Anodal stimulation could have increased the kind of bottom-up signaling that leads to restructuring, perhaps by mimicking activity that typically occurs when rASTG is first starting to effectively integrate coarse semantic fields, during intuitive processes.

4.3.3 Why no effects on insight solution production?

If increasing rASTG activity with anodal stimulation helped with coarse semantic integration and progress toward insight, why was anodal stimulation not associated with more insight solutions than cathodal stimulation? It is possible that increasing integration of semantic associations only speeds insight solutions or makes them less likely to be erroneous, but does not yield more solutions because the limiting factor is the strength or presence of the semantic association itself. If you have never heard of the term *goosestep,* even with the most efficient semantic integration possible you are unlikely to integrate semantic fields to solve the CRA problem: [bump/egg/step → goose].

An alternate explanation is that the direct effects of anodal stimulation that serve to enhance insight processes, perhaps by increasing the likelihood or speed of semantic integration, could have been counterbalanced by anodal stimulation's disruptive effects on analysis. It is generally thought that when first approaching insight problems, solvers work through the initial problem space with search strategies prior to reaching impasse and then they restructure (Ash & Wiley, 2006). Disrupting analysis via increased hemispheric inhibition may have interfered with initial analytic processing of problem stimuli, which could have obstructed insight by preventing problem stimuli from being correctly understood or identified, or by preventing sufficient exploration of the initial problem space, which may have reduced impasse and failed to provoke restructuring.

4.4 Error rates

4.4.1 Commission errors and the role of rASTG

Error rates can provide information about the role of rASTG in insight, specifically the degree to which rASTG activity contributes to achieving the insight solution rather than merely preceding insight solution indication in an epiphenomenal manner. The finding that anodal stimulation of rASTG had no effect on insight commission errors (when participants indicated they had solved the problem, but said an incorrect answer), combined with the finding that cathodal stimulation was associated with increased insight commission errors, supports the idea that rASTG activity is associated with the production of solutions that are identified as insights rather than just serving as a mechanism to indicate solution has been achieved.

If the right ASTG serves primarily an alert role for insight solutions, one might expect that interfering with it with either anodal or cathodal stimulation would lead to fewer insight solutions because a failure of an alert mechanism would presumably lead participants to occasionally fail to indicate solutions even when they had achieved them. That was not the case with either anodal or cathodal stimulation, however because commission error rates changed (as did solution speeds, see below), there were different effects of the two types of stimulation on insight solution, which suggests that the solution process itself was affected, not merely the response bias.

The increased number of insight errors of commission associated with cathodal stimulation was especially interesting given that participants were explicitly instructed that insight is partially defined by a feeling of certainty regarding solution correctness. Although participants presumably still felt certain that their answers were correct when receiving cathodal stimulation, insight commission error rates were more than 200% higher than during anodal stimulation. Presumably cathodal stimulation interfered with right hemisphere semantic integration processes, which due to the inaccessibility of right hemisphere problem solving processes, led participants to indicate a solution when only a partial solution or a completely incorrect solution had been achieved.

4.4.2 Omission Errors

Right hemisphere solution progress is not amenable to meta-analysis (Metcalfe & Wiebe, 1987; Ben-Zur, 1989; Smith & Kounios, 1996). Therefore, if anodal stimulation merely biased solvers to use insight strategies (attempting to integrate nondominant semantic associations), failure would be more likely to result in an omission error, as opposed to a commission error, because the solver would have no conscious knowledge of solution proximity. Unfortunately, because participants are only asked which solution strategy they used after they make a response, the experimental design prevents an examination of solution strategies that were employed prior to timeouts.

4.4.2 Higher error rates

It is possible that activity in the anterior cingulate cortex (ACC), which has been associated with error detection and performance monitoring (MacDonald, Cohen, Stenger & Carter, 2000), failed to bias responding against commission errors of insight during cathodal stimulation because participants were given no feedback regarding the accuracy of their solutions. The lack of feedback may also explain the fact that error rates seen in this experiment were generally higher in all conditions compared with other investigations using similar paradigms (Jung-Beeman et al., 2004; Kounios et al., 2006; Cerruti & Schlaug, 2009). However, because there was no feedback in the anodal stimulation condition either, the lack of feedback does not explain the difference in commission error rates between stimulation conditions.

4.4.3 Analysis errors

Due to the smaller number of analysis solutions and errors, individual analysis error rates had more variability. Participants in the anodal stimulation condition committed errors on 27.6% of all responses classified as analysis, compared to 20.4% for sham stimulation (figure 16). This significant 35% increase in analysis errors associated with anodal stimulation could be attributed to the same two dynamics used to explain the increase in insight percentage: 1) an increase in interhemispheric rivalry could have interfered with left ASTG-mediated semantic integration processes; 2) increased rASTG recruitment of anterior meta-cognitive attentional mechanisms could have deprived the left hemisphere search process of needed frontal resources, which may have led to erroneous responding.

4.5 Solution Speeds

4.5.1 Insight solution speeds

During the solution of CRA problems, the hypothesized semantic integration role of the ASTG is thought to be bilateral and simultaneous (Jung-Beeman, 2005). However, when non-dominant meanings of a word are needed to yield a solution, such as in the case of the CRA problem: [right, cat, carbon → copy], at some point the solver has to detect an overlap in semantic association fields between "copy" with "right" to obtain the solution compound copyright, and overlook dominant semantic associations such as right vs. left and right vs. wrong. This is the process of overcoming blocking or impasse and restructuring the solution strategy so that nondominant right hemisphere associations are attended to. If right hemisphere anodal stimulation increased inhibition of left hemisphere analytic/search processes via an increase in hemispheric rivalry, the dominant representations of the left hemisphere may have been less easily detected and elaborated. This may have led the problem solver to perceive exhaustion of search or blocking before all possibilities has been considered. Consequently some associations could have been more easily ignored, which would increase the sense of blocking and prompt restructuring faster. In this scenario, cathodal stimulation could have achieved its slowing effects on insight solution speeds by disinhibiting left ASTG activity and increasing the semantic integration of the incorrect dominant associations, thus increasing the number of dominant associations that had to be considered, delaying impasse and preventing insight from occurring as rapidly.

Although up to this point speculation about the effects of stimulation has been limited to ASTG, based on the location of the reference electrode posterior to the rASTG, it is quite likely that some current flowed posteriorly, which could also have altered activation of semantic associations in right posterior medial temporal gyrus (Jung-Beeman, 2005). While the polarity of this current and the nature of its downstream effects is speculative, if anodal stimulation increased right posterior-MTG-mediated semantic activation, solution-relevant nondominant associations may in turn have been more easily detected, which could have facilitated insight solution speed.

Burgess and Simpson (1988) used lexical priming to find that in the right hemisphere there was a slow, long-lasting increase in activation for the subordinate meanings of words, while in left hemisphere the rate of activation increase for subordinate meanings was faster but activation was inhibited fairly quickly. Perhaps the mechanism by which insight solution speed was increased with anodal stimulation and decreased with cathodal stimulation was that stimulation altered the initial speed of non-dominant semantic activation via effects on right posterior medial temporal gyrus.

4.5.2 Analysis solution speeds

Although this investigation was primarily designed to explore how targeted stimulation affected the insight process, because insight and analysis are likely interdependent processes, a follow-up exploration of stimulation effects on analysis solution times was pursued. Anodal stimulation was associated with faster analysis solution speeds and cathodal stimulation was associated with slower analysis solutions speeds. Such a result at first seems counter-intuitive. According to hemispheric rivalry theories, excitatory stimulation of the right ASTG should interfere with left-hemisphere-driven search/analysis (see figure 18), which one might assume would slow analysis solution speed, not increase it.

One explanation for faster analysis speeds during anodal stimulation is that stimulation of the rASTG caused premature restructuring via recruitment of anterior attentional resources away from dominant left ASTG semantic integration processes. Thus CRA problems that would have taken longer to solve (and increased the mean solution time) either were not solved (timeouts) or were solved with insight. The fact that fewer problems were solved with analysis during anodal stimulation provides some support for this explanation. Another possibility is that increased interhemispheric inhibition of left posterior temporal cortex (possibly due to anodal current shunting through the contralateral homolog) essentially reduced noise more than signal for dominant semantic associations, thus making them even more salient and detectable. This explanation is supported by unpublished findings (Jung-Beeman, personal communication, 2011), in which less bilateral hemodynamic activity in posterior temporal areas was associated with CRA solution search.

Hemispheric rivalry theories would also suggest that cathodal stimulation of rASTG would disinhibit analysis processing, which could increase analysis speeds or at least show no effect. Yet during cathodal stimulation, analysis solutions were slower than during anodal stimulation. There are a few possible explanations for this finding: 1) disinhibiting the left ASTG via reduced interhemispheric inhibition may have actually interfered with the analytic process in some fashion and delayed integration of dominant associations, an explanation that is supported by the finding that cathodal stimulation caused a slight (non-significant) reduction in analysis solutions. 2) Contralateral cathodal stimulation may have increased activity in left ASTG, which blocked the solver by increasing impasse, perhaps via increased elaboration of fine semantic associations, thus preventing participants from shifting attention to less dominant associations and slowing analytic solution speed.

4.5.3 General speeding effect of anodal stimulation?

There is also the possibility that there was a general enhancement of CRA solution speed caused by anodal stimulation, regardless of strategy, and a general slowing of CRA solution speed caused by cathodal stimulation, regardless of strategy. While it is true that the average CRA problem was solved faster with anodal stimulation than cathodal stimulation, two findings support the idea that anodal stimulation differentially affected analysis and insight processes. The first is the difference in commission error rates: anodal stimulation was associated with higher analysis error rates and lower insight error rates. The second finding that supports a theory of strategy-specific effects of stimulation on solution speed is the fact that fewer analysis solutions were produced during anodal stimulation, yet the number of insight solutions was unchanged. That result would seem less likely if anodal stimulation was speeding CRA solution processes in general.

4.6 Insight and Recall of CRA solutions

The hypothesis that insightful solutions to CRA problems would be recalled better was not supported by the results. There could be several reasons for this negative finding. The most obvious explanation is that there was no effect to detect. This investigation really cannot answer that question due to a lack of power in the design. Another difficulty in detecting an effect could be the unexpectedly high rate of insight responding in the first session, which could have obscured typical variance in recall predicted by solution strategy due to ceiling effects. If most of the solutions are produced via insight, it would be hard to show a benefit of insight for recall. The fact that participants did not know they would have recall assessed likely did not interfere with beneficial effects of insight on recall. One would presume that during an explicit recall task a participant would be attempting to remember solutions as well as the process by which they were achieved in order to provide more contextual cues for recall, which presumably would benefit recall of solutions achieved with analysis due to solvers' disproportionate access to solution process information compared with insight solutions. This null finding is also in accord with previous unpublished research investigating insight's effect on recall (Jung-Beeman, personal communication, 2011). In investigations conducted by Jung-Beeman and colleagues, recall of solution words was not aided by insight, however recall of solution compounds (crabapple, rather than apple for the CRA problem Pine, Crab, Sauce→ apple) was aided by insight. If one considers that the insight itself was related to the integration of non-dominant semantic associations into a compound word (pineapple), presumably the advantage of affect, and whatever other qualities of insight might benefit recall, would be centered on the final compound word that completed the triad rather than the solution that fit all three cue words.

4.7 Limitations

4.7.1 Shifting strategies during the course of the experiment

One finding of potential concern in the interpretation of this data has been that participants used more insight during the first session (~75%) than during the third session (~60%). This effect was larger than any effect of stimulation and was not anticipated. However, when Bowden and Jung-Beeman (2003a) presented the initial set of 144 CRA problems, they suggested the possibility that solvers would alter their strategies over time. They suggested that experience with insight problems might sensitize problem solvers to cues and heuristics, and thus reduce the affective experience of insight. The affective experience of insight for has already been shown to not be as powerful for CRA problems as it is for more complex insight problems (Bowden & Jung-Beeman, 2007). Although Bowden and Jung-Beeman (2003a) did not state that desensitization to the affective aspect of insight would be a problem in the course of a single experiment, it may have occurred over the course of several sessions. Also, over the course of multiple sessions, participants may have begun to develop solution systems that relied on more search or analytic strategies, or they may have improved in their ability to exploit heuristics, which may have biased them toward analytic techniques and/or improved the efficiency with which they applied those techniques.

It is also possible that the recall task had an effect on solution strategy and induced the participants to actively think about how to recall the items from subsequent sessions, despite having been instructed that it would not be necessary. However, preliminary analyses comparing insight solution percentages during sham for those who had recall assessed during session 1 and those who did not, suggested that recall did not affect subsequent strategy selection.

The change in strategy over sessions could also be attributed to directions given to the participants. Insight was described as a process in which “you do not know how you achieved the answer.” That description may have caused them to increasingly try to examine their meta-cognitive processes across sessions, which according to verbal-overshadowing theories could have biased them against using insight (Koestler, 1964; Schooler & Melcher, 1995). A more plausible explanation is that participants may have began to interpret the directions to mean that any type of analytic (search) strategy would disqualify the solution from being an insight, despite the presence of other hallmark signs of insight processing such as certainty and the ‘aha’ experience.

4.7.2 Visual Search

Past studies have found that overall solution rates of CRA problems were higher than those reported here (Jung-Beeman et al., 2004; Kounios et al., 2006). Even the possibly unsettling effects of direct current stimulation on one’s ability to solve such problems cannot fully explain the discrepancy, because in a study by Cerruti and Schlaug (2009) in which DCS was given to the left PFC while participants solved CRA problems, the investigators reported overall CRA solution percentages of 50%.

An explanation for the lower solution rates and a possible limitation of the study was the use of 10 minutes of visual search prior to CRA solution. At approximately 1 second per search, it is an intensive task to engage in for 10 minutes. Inclusion of the visual search task was motivated by the need to conserve CRA problems while participants acclimated to stimulation, the need to control pre-stimulation activity, and a desire to study the onset effects of stimulation of rASTG, which has been demonstrated to be involved in such a task. (Results not reported here.) It is possible that extensive activity of the rASTG prior to attempting insight problems led to fatigue effects, or the loss of cognitive reserve, which diminished subsequent CRA solution rates. Because the synaptic effects of direct current stimulation that begin to take hold after a few minutes (see figure 5), are mediated through LTP-like mechanisms (Liebetanz et al., 2002; Nitsche et al., 2004c; 2008), and because homeostatic plasticity theories (Bienenstock, Cooper, & Munro, 1982) suggest that vigorous activity in a cortical area can increase LTP thresholds (Zhang & Linden, 2003; Ziemann et al., 2004), it is also possible that visual search prior to CRA solution diminished the effects of anodal stimulation on CRA problem solving.

4.7.3 Lower solution rates

In addition to the effects that the visual search task may have had on overall CRA problem solution, there was also a lack of feedback regarding errors, discussed earlier, which may have made participants more likely to respond aggressively and commit errors.

Another possible explanation for the decreased number of solutions reported here compared to previous research is that 186 CRA problems were used in the this investigation. The set included the 144 CRA problems with normative data published by Bowden & Jung-Beeman (2003a) as well as an additional 42 problems provided by the same researchers. Other investigators chose smaller sets and may have used an easier group of problems.

4.7.4 High performing participant population

Given that the participants were students affiliated with a highly competitive school (the University of Pennsylvania), some of their problem solving skills and verbal fluency may be operating closer to peek capacity than participants from other populations. Therefore, it may have been more difficult to enhance the use of insight strategies in these participants than it would have been to alter solution strategies in other populations.

4.7.5 Interpretation of stimulation effects

As described in Methods (section 2.5.2), although anodal stimulation typically hypopolarizes underlying neural membranes and cathodal stimulation hyperpolarizes them, the arrangement of the underlying cytoarchitecture can greatly determine the effects of stimulation (Creutzfeldt, Fromm & Kapp, 1962). Neurons with axons extending parallel to current flow may be affected differently then those with axons aligned perpendicular to the flow of current. There is also the complication of the reference electrode placement and whether it is truly inert under the ipsilateral mastoid. Interpretation of the effects of stimulation is also confounded because it is unknown whether the underlying cortical tissue is serving a primarily excitatory or inhibitory function with regard to the behavior in question. Along with unpredictable current shunting in the brain (Sadleir, Vannorsdall, Schretlen & Gordon, 2010), it can be difficult to ascertain for certain what effects stimulation is having on underlying tissue, which can complicate interpretation.

4.7.6 Unilateral stimulation and lateralized processes

Although investigating supposedly lateralized functions with unilateral brain stimulation would seem straight forward, inter-hemispheric inhibition phenomena produce uncertain effects in the contralateral homolog. In the case of ASTG integration of semantic associations during solution of CRA problems, that stimulation likely affects the implementation of both insight and analysis strategies, which complicates interpretive efforts.

5. CONCLUSIONS

This investigation supported previous functional imaging and electrophysiological studies that implicated the right anterior superior temporal gyrus in insight processes. Direct current stimulation's effects on insight solution speed and accuracy suggest that rASTG has an active role in problem solving with insight and it is unlikely that rASTG activity is epiphenomenal to insight solution. Influencing activity in the rASTG seems to have directly affected insight processes, specifically solution times and commission errors. The effect of stimulation on insight is likely due to altered integration of nondominant semantic associations, or via contralateral effects on impasse (caused by difficult-to-ignore dominant semantic associations), or altered recruitment by rASTG of anterior meta-cognitive attentional resources, or (most likely) a combination of those mechanisms and others.

The possible role of rASTG activity as an alert mechanism indicating the presence of an insight solution was not supported. If the gamma activity shown in previous investigations to occur in the rASTG 0.3 s prior to indication of insight (Jung-Beeman et al., 2004) was merely a signal that a solution had been achieved, one might expect that the same type of stimulation that increased insight solution speed would have increased commission errors. The fact that anodal stimulation increased insight speed and did not increase insight commission errors, while cathodal stimulation was associated with slower solutions and more commission errors, suggests that stimulation was affecting the solution production process, rather than biasing response.

There were also significant effects of ongoing exposure to CRA problems, particularly a large effect on insight solution strategies and a reduction in errors over the course of 3 sessions. This may imply that in some situations, people learn to solve verbal problems over time with more analytic strategies and rely less on insight as a tool as they grow accustomed to a problem space.

The results reported here also suggest that analytic strategies may be more easily perturbed by stimulation than insight strategies. Certainly with regards to production of solutions this seems to be true. It may be that what makes analysis both effortful and amenable to meta-cognitive processes is also what makes it more vulnerable to disruption, namely the likely dependence on working memory and other conscious frontal processes required to hold semantic associations in mind while different candidates are tried. Perhaps meta-cognitive attention is as distractible as externally focused attentional resources.

Although this study did not find evidence that insight benefitted recall, it was underpowered to do and was likely assessing the wrong dependent variable (solution word rather than solution compound), so the potential of such a relationship cannot be discounted.

5.1 Future Directions

Previous research has shown that the ability to solve CRA problems is correlated with the ability to solve more complicated insight problems and is likely correlated with aspects of creativity. This investigation demonstrated that direct current stimulation can be used to alter participants' solution strategy (insight vs. analysis) and can influence the effectiveness of those strategies, which may have implications for enhancement of problem solving and creativity.

These findings suggest that direct current stimulation could be used in a targeted time-limited way to facilitate solution of important real-world problems in non-clinical populations, potentially by assisting the solver in overcoming impasse or abandoning ineffective analytic strategies.

The portability, safety, simplicity, and affordability of direct current stimulation devices support its potential use as an assistive problem-solving device in some clinical populations, particularly those who perseverate with repeated application of ineffective problem-solving strategies, such as patients with traumatic brain injury and dementia. TDCS might be used to interrupt impasse or fixedness and allow patients to approach a problem differently, perhaps relying on insight mechanisms to solve more common problems of everyday functioning. With regards to clinical applications, another advantage of tDCS is that some investigations have shown that with a few repeated stimulations (Rigonatti et al., 2008; Reis et al., 2009), effects can be long lasting (months), which implies that patients might only need to use the device for a limited amount of time before long-term plastic changes began to facilitate the desired behavioral changes.

Before tDCS can be used to enhance insight problem solving, more foundational research must be completed. Future investigations will need to elaborate on the findings reported here, which will require a greater understanding of the mechanisms of insight and analysis solutions of verbal problems and how such solution strategies can be altered.

In order for direct current stimulation to continue to develop as a technique for research and clinical purposes, more parametric studies are desperately needed. With the exception of the fine work that Nitsche and colleagues have pursued over the past 12 years (Nitsche & Paulus 2000; 2001; Nitsche, 2008 for a review), few other investigators are systematically studying direct current stimulation effects. Most such work has been accomplished by targeting motor cortical areas. Parametric studies of tDCS effects in temporal cortex and other locations are needed to provide guidance for proper study design.

A potential follow-up to this investigation would be to stimulate left ASTG in the same manner that rASTG was stimulated in this investigation. This could provide a better understanding of the strength of interhemispheric rivalry effects compared with direct ipsilateral effects of stimulation. It could also improve our understanding of the degree to which insight processes are more or less robust than analytic processes when the hemispheric balance is perturbed by stimulation.

Another experiment to extend and support some of the findings reported here would be to stimulate bilateral ASTG by placing the reference electrode over the left ASTG. While such placement complicates interpretation, based on the robust effect sizes reported by Chi & Snyder (2011), such a montage may greatly exaggerate effects in both hemispheres, which could ultimately be more clinically effective for altering problem-solving strategies.

There is evidence that alternating current stimulation can increase the power with which underlying neuronal assemblies oscillate at the frequency of stimulation. The entrainment effect of transcranial alternating current stimulation (tACS) does not seem limited to certain frequencies; it has been shown at delta (Marshall et. al., 2006), alpha (Zaehle, Rach & Herrmann, 2010), and at ripple speed (>100 Hz) (Siebner & Ziemann, 2010). Based on the fact that EEG recorded gamma frequency activity in rASTG during insight (about 0.3 s prior to indication of insight solution, Jung-Beeman et al., 2004), potential additional investigations could be pursued with tACS set to 50 hz at rASTG. Another possibility for a tACS intervention could be to stimulate right posterior parietal cortex with 12-14 hz stimulation (alpha), activity that was shown to precede insight responding by 1.4 s (Jung-Beeman et al., 2004). However, because both the alpha and gamma bursts prior to insight were short-lived, enhancing either type of activity might only affect the expediency with which insights are reached. In order to make an insight more likely, it might be more useful to target preparatory mechanisms. With this in mind, bilateral tACS stimulation with large electrodes (100 cm^2, such as those used for reference in some tDCS experiments), could instantiate the widespread alpha activation in occipital areas that predicts subsequent successful solution of CRA problems with insight (Kounios et al., 2006).

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APPENDIX A: FIGURES

Figure 1. 9-Dots problem

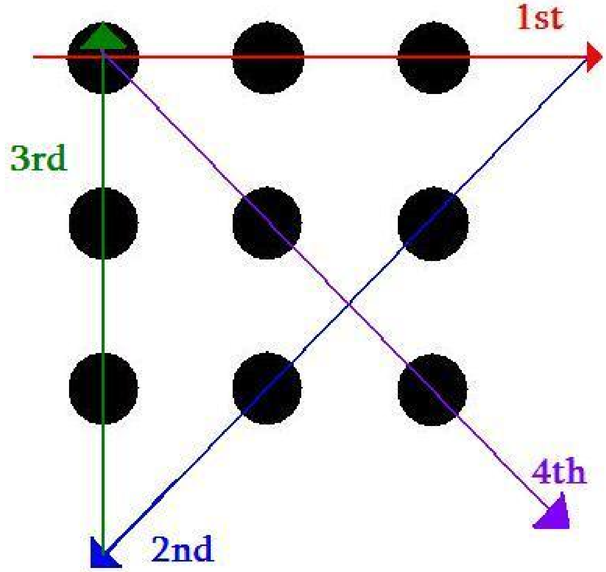


Figure 2: Matchstick addition problems

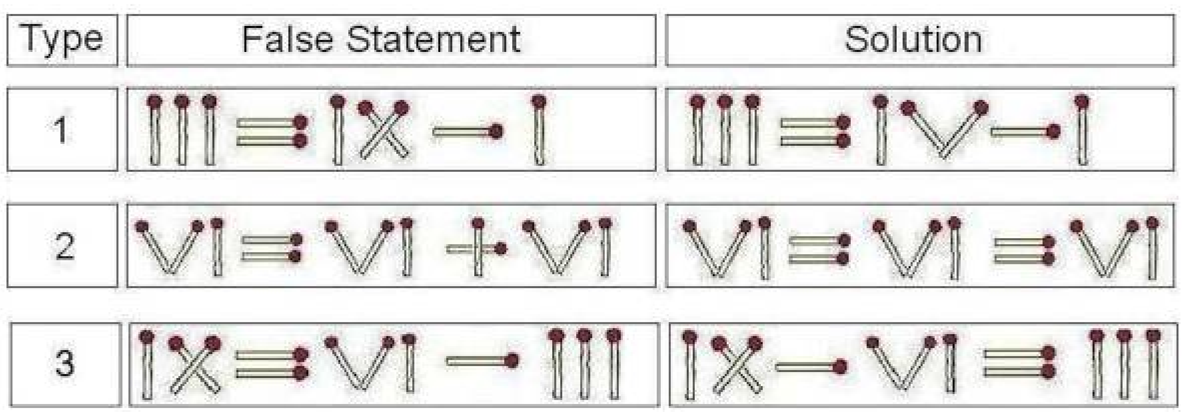


Figure 3. Visual Search

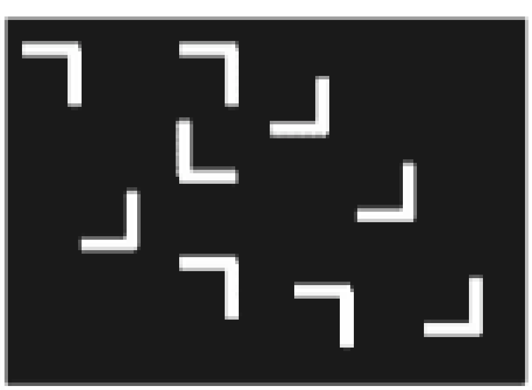
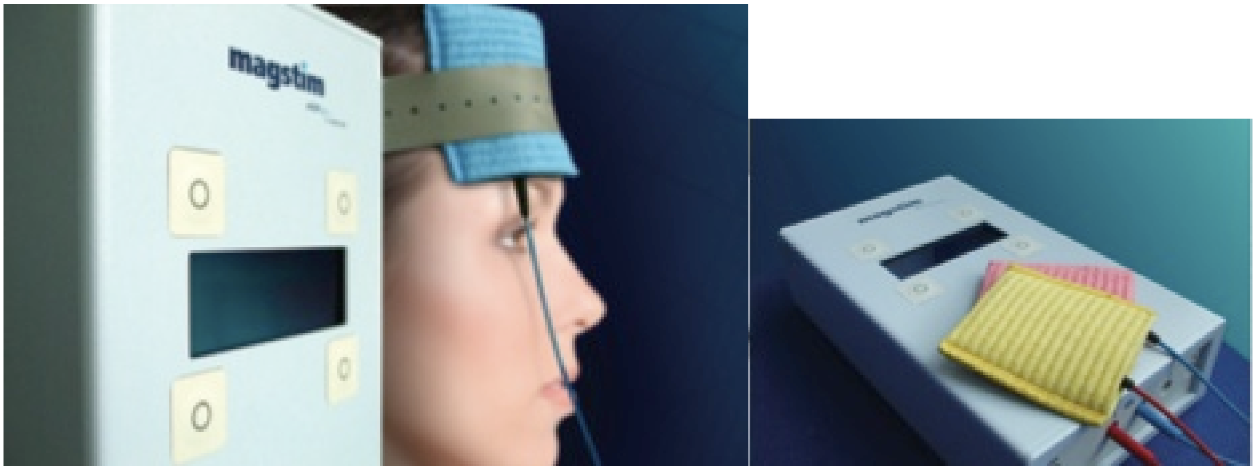


Figure 7: The Magstim Eldith Stimulator^{Plus}



APPENDIX B: ONLINE VS. OFFLINE

B.1 Online and offline effects of tDCS during CRA problem solution

There are very few published studies that have compared active stimulation and the after-effects of stimulation (offline) on the same behavior. Typically, noninvasive brain stimulation studies examine either all online or all offline effects. If the behavior of interest does straddle the end of stimulation, rarely are the different effects noted. Stimulation status seemed to significantly modify two dependent variables of particular interest to this investigation: insight error rates and insight response time.

B.1.1 Insight solution speeds (online)

Insight solution speeds seem most responsive to active (online) stimulation, with cathodal stimulation slowing insight solutions and anodal stimulation increasing speeds. Repeated measures ANOVA with stimulation order as a covariate and taking the log of the solution speed, showed that the difference between online insight solution times during anodal stimulation compared to early sham was not significant; F(19)=.214, p=.649. There was a marginally significant difference between online cathodal stimulation and early sham; F(19)=3.903, p=.064. But because both types of stimulation altered solution speeds in opposite directions, there was a significant difference between insight solutions speeds during online anodal

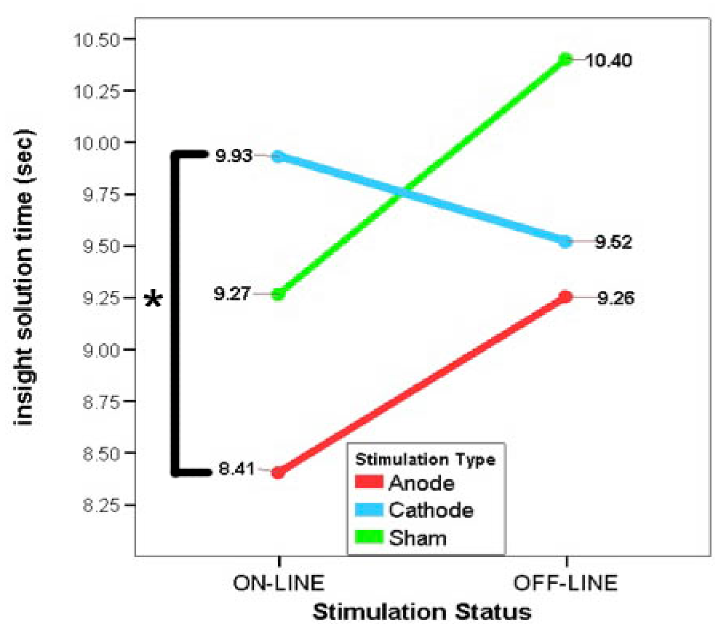


Figure 20: changing insight solution times after stimulation ends

stimulation compared to online cathodal stimulation, F(19)=8.207, p=.010, figure 20. It is more difficult to understand what happens after stimulation ends. It appears that in general solution speeds slow a bit, perhaps due to fatigue, over the course of a session. The advantage in speed is maintained when anodal stimulation is offline, consistent with previous findings that behavioral effects tend to last at least as long as the period of stimulation (Nitsche, 2000). The increase in speed with which participants solve insight problems after cathodal stimulation suggests that there could have been a rebound effect, in which participants may have been suddenly able to allocate some unknown cognitive resources after cathodal stimulation ended. It is a fairly large change, if one considers the magnitude of the fatigue effect.

B.1.2 Insight error rates

The effect of anodal stimulation on error rates also seems to fade after stimulation ends. The decline in error rates for cathodal stimulation from online to offline has a similar slope to sham stimulation, but there is a bit of a rebound in anodal situation. A repeated-measures ANOVA comparing online insight error rates found a significant difference between means, F(19)=3.696, p=.034. The only significant difference in error rates is between online cathodal stimulation (15.1%) and anodal stimulation (6.3%), t=-2.123, p=.047.

In general, the effects of anodal stimulation seemed to linger more than those of cathodal stimulation. Generally, the results were mixed, depending on the variable examined. Offline effects of

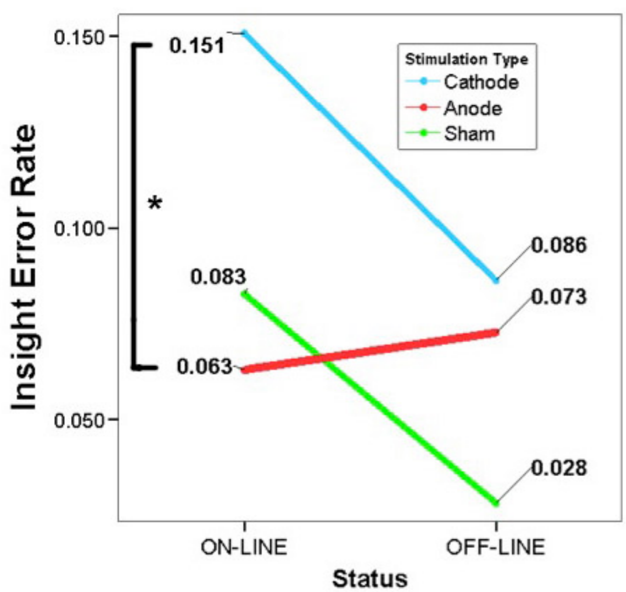


Figure 21: Insight Error Rates

anodal stimulation sometimes rebounded and sometimes lingered. Offline effects of cathodal stimulation tended to fade rapidly.

APPENDIX C: INCLUSION/EXCLUSION FORM

Inclusion and Exclusion Criteria Checklist

Transcranial Direct Current Stimulation Investigations of Cognition and Action

Protocol #809185

ID #: ______________________ Date: ____________________

Age: ______________________ Sex: ____________________

Years of Education: ____

Left handed ______ Right handed ______

Race/Ethnicity: ______________________

***Inclusion criteria**:* (*Must answer* **yes** *to all questions to be eligible for participation*)

Does the subject satisfy the following criteria?

English speaker at an early age	Yes	No
$\geq$ 7 years of education	Yes	No
The patient is able to understand the nature of the study, and give informed consent.	Yes	No
If female, the patient has been informed that she cannot receive tDCS if she is pregnant and that if she cannot rule out pregnancy then a pregnancy test will be conduced prior to inclusion in the study.	Yes	No

***Exclusion criteria**:* (*Must answer* **no** *to all questions to be eligible for participation*)

Does the subject have any of the following:

History of significant neurologic or psychiatric disease?	Yes	No
Current consumption of anti-convulsant, anti-psychotic or sedative/hypnotic medications?	Yes	No
History of seizures?	Yes	No

Condition: ______________________

Test: ______________________

APPENDIX D: PAYMENT RECEIPT

PAYMENT RECEIPT

This document is my signed affirmation that I have been compensated in the amount of _________ for _______ hours of participation in the project entitled "Direct Current Stimulation of Right Anterior Superior Temporal Gyrus During Solution of Compound Remote Associates Problems" under University of Pennsylvania Protocol #809185.

My participation was on: ________ / _________ / 20___________.

The research was conducted by _______________________________.

The covering neurologist was ________________________________.

____ _________________

Participant Name Date

APPENDIX E: EDINBURGH HANDEDNESS INVENTORY

Edinburgh Handedness Inventory

1. Which hand do you use for writing?

◊ Left ◊ Both ◊ Right

2. Which hand do you use for drawing?

◊ Left ◊ Both ◊ Right

3. Which hand do you use for throwing?

◊ Left ◊ Both ◊ Right

4. Which hand do you use for scissors?

◊ Left ◊ Both ◊ Right

5. Which hand do you use to hold the toothbrush when you brush your teeth?

◊ Left ◊ Both ◊ Right

6. Which hand do you use to hold a knife (without fork)?

◊ Left ◊ Both ◊ Right

7. Which hand do you hold a spoon with when you are using it?

◊ Left ◊ Both ◊ Right

8. Which hand do you use with a broom (upper hand)?

◊ Left ◊ Both ◊ Right

9. Which hand do you use to hold a match when you strike it?

◊ Left ◊ Both ◊ Right

10. Which hand do you use to grab the lid to open a box?

◊ Left ◊ Both ◊ Right

APPENDIX F: UNIVERSITY OF PENNSYLVANIA CONSENT FORM

University of Pennsylvania
Informed Consent Form

IRB Approval From: 12/09/10
IRB Approval To: 12/08/11

Transcranial Direct Current Stimulation Investigations of Cognition and Action

Protocol Number: 809185

Principal Investigator:
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Philadelphia, PA 19104
(215)
Roy.Hamilton@uphs.upenn.edu

24-Hour Emergency Number:
(215) 662-6059
Ask for Neurology Resident on Call

You are being asked to take part in a research study. This is not a form of treatment or therapy. It is not supposed to detect a disease or find something wrong. Your participation is voluntary which means you can choose whether on not to participate. If you decide to participate or not to participate there will be no loss of benefits to which you are otherwise entitled. Before you make a decision you will need to know the purpose of the study, the possible risks and benefits of being in the study and what you will have to do if you decide to participate. The research team is going to talk with you about the study and give you this consent document to read. You do not have to make a decision now; you can take the consent document home and share it with friends, family doctor and family.

If you do not understand what you are reading, do not sign it. Please ask the researcher to explain anything you do not understand, including any language contained in this form. If you decide to participate, you will be asked to sign this form and a copy will be given to you. Keep this form, in it you will find contact information and answers to questions about the study. You may ask to have this form read to you.

What is the purpose of the study?

You are invited to participate in an experiment involving transcranial Direct Current Stimulation (tDCS), a technique by which small electric currents are applied to the scalp.

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The study will test whether very small amounts of electricity applied to the scalp affect a person's ability to recognize and recall words and objects as well as their perception and reaction times when tested with the help of a computer program. To do this, we will study the effects of tDCS on your ability to perform such tasks as naming, reaching, or depressing key as quickly as possible. The purpose of this research is to learn about the specific brain regions that are involved in these behavioral tasks.

Why was I asked to participate in the study?

You are being asked to join this study because you are what we refer to as a normal subject. This means you have no history of previous neurologic disease such as a seizure or stroke or psychiatric disease and are not taking medications for seizures or psychiatric problems.

How long will I be in the study? How many other people will be in the study?

You will be one of between 400 and 500 people in the study over the course of 4 years.

Different experiments will require different amounts of time. Some experiments involve only 1 session of about 1 hour whereas for other studies you may be asked to participate in up to 4 sessions of 1 hour each. Visits will be scheduled at your convenience. You will always be free to stop any study at any time.

Where will the study take place?

You will be asked to come to a research laboratory in the Hospital of the University of Pennsylvania, in a laboratory at the School of Medicine or at Ralston House, a building on the Penn campus.

What will I be asked to do?

If you decide to participate, Dr. Coslett or a designated representative will describe the procedures to you. You will be asked to perform a variety of behavioral tasks before, during or after tDCS. The specifics of the task will differ but none of the tasks are painful or risky. For example, in one task you might be asked to push a button when you see a certain word or picture. In another task, you might be asked to read a list of words and say at a later time whether a word spoken to you at that time was one of the original list of words that you read. In yet another task you might be asked to reach with your hand to pick up or point to an object such as a cup or pen.

A second component of the study is brain stimulation with transcranial Direct Current Stimulation. In this technique a small direct current (approximately 1 to 1.5 mA) is delivered to the scalp for up to 20 minutes. The current is approximately what one might expect from a 9 volt battery. The amount of current to be delivered will be at a level that is a small fraction of the level that has been determined to be safe in animals; for example, the maximal total charge to which you might be exposed (.054C/cm2) is approximately 4,000 times less than the current that caused problems with animals.

Many experiments will also include a sham stimulation condition, in which a small current will be delivered only at the beginning of the test. The current is produced by a small portable machine that is connected by thin wires to two salt-water soaked pads that are placed on your head and held in place with a strap. The location of the salt-water soaked pads will vary depending on the experiment but one pad is likely to be on your forehead and another at a different location on your scalp. The pads will be present for 10-20 minutes, depending on the study. You will probably feel tingling of your scalp at the start of the current; this is normal and expected. You are consenting to participate in one experiment that may have multiple sessions. Should you desire, you will also be able to participate in other experiments with tDCS; in the event that you participate in another experiment, the new experiment will be described and you will be asked to sign another Informed Consent document.

What are the risks?

Behavioral Testing

The behavioral tasks involve minimal risk. You may be asked to perform a task that you find very difficult or irritating. If you find the task too annoying or frustrating the experiment will be discontinued.

Transcranial Direct Current Stimulation

In published studies using this technique there have been no reported significant side effects from tDCS. This means that tDCS has never been associated with reported seizures, loss of consciousness, or weakness, numbness or pain that did not go away. The most commonly reported side effects of TDCS are a mild tingling in the skin underlying the electrodes, itching under the electrode, and mild pain. Some subjects report feeling fatigued after tDCS. Finally, there is a chance the machine could cause a small electrical shock. The amount of tDCS we will employ is well below the level considered to be safe. Also, although adverse effects are considered to be unlikely to occur, a neurologist will always be present or available within 5 minutes should any problems arise.

In many experiments you will be asked to undergo tDCS on multiple occasions. There is at present no evidence that repeating tDCS is associated with increased risk. For the sake of caution, however, you will not be permitted to have tDCS more than once daily and no more than three times in one week.

Pregnancy
There is no known risk to a mother or fetus from tDCS; because the safety of the technique in pregnant women has not been fully studied, however, pregnant women are not permitted to participate in the study. Women of child-bearing age will be asked to undergo a urine pregnancy test before participating in the study.

How will I benefit from the study?

There is no benefit to you. However, your participation could help us understand more about what parts of the brain are important for cognition, action and perception. The

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studies that we do with tDCS may offer insights that may ultimately lead to techniques to improve brain function or treat brain problems. tDCS has been demonstrated to improve performance of normal subjects and may have benefits for clinical populations.

What other choices do I have?

Your alternative to being in the study is to not be in the study.

What happens if I do not choose to join the research study?

You may choose to join the study or you may choose not to join the study. Your participation is voluntary.

There is no penalty if you choose not to join the research study. You will lose no benefits or advantages that are now coming to you, or would come to you in the future. The research team will not be disappointed or angry should you choose to not participate.

If you are currently receiving services at the Hospital of the University of Pennsylvania and you choose not to volunteer in the research study, your services will continue.

When is the study over? Can I leave the study before it ends?

The study is expected to end after all participants have completed all visits and all the information has been collected. The study may be stopped without your consent for the following reasons:

- The study doctor feels it is best for your safety and/or health-you will be informed of the reasons why.
- You have not followed the study instructions
- The PI, the sponsor or the Office of Regulatory Affairs at the University of Pennsylvania can stop the study anytime

You have the right to drop out of the research study at anytime during your participation. There is no penalty or loss of benefits to which you are otherwise entitled if you decide to do so. Withdrawal will not interfere with your future care.

If you no longer wish to be in the research study, please contact Dr. Coslett, at hbc@mail.med.upenn.edu or (215) 349-8585 and take the following steps:

- State that you would like to withdraw from the study.
- If you have any pending appointments, contact the study coordinator, Jennifer Benson, jebenson@mail.med.upenn.edu or (203) 258-6642. State that you are withdrawing from the study, so that she can cancel your sessions.

How will confidentiality be maintained and my privacy be protected?

The research team will make every effort to keep all the information you tell us during the study strictly confidential, as required by law. The Institutional Review Board (IRB) at the University of Pennsylvania is responsible for protecting the rights and welfare of research volunteers like you. The IRB has access to study information.

Your confidentiality will be maintained by keeping records in a secure location. Most of the information will take the form of computer files; these will be de-identified by using a coding process under which subjects are identified by two initials and the date of the testing. Subject names, ages and ethnicity will be recorded only in a secure, password-protected computer location. In addition, the following precautions will be exercised in protection of your confidentiality.

- Paper-based records will be kept in a secure location and only be accessible to personnel involved in the study.
- Computer-based files will only be made available to personnel involved in the study through the use of access privileges and passwords.
- Whenever feasible, identifiers will be removed from study-related information.

In some tasks requiring language production, you may be recorded in a digital fashion for later analysis. The digital files will be destroyed after the experiment is completed. Also, in order to determine if you will be disqualified by virtue of neurologic or psychiatric issues or current consumption of certain medications, you will be asked a variety of questions about your medical history; should you not be eligible to participate, details of this information will not be recorded. If you are eligible, the information will be recorded only as checks on a patient eligibility checklist. The only protected health information (PHI) that will be collected from you includes your name, address, contact information and Social Security number. This information will be stored in a protected computerized subject database. Protected health information will not be disclosed to anyone not directly involved in the study.

What happens if I am injured from being in the study?

If you are injured and/or feel upset and emotional discomfort while participating in the study you may contact the PI or the emergency contact name on the first page of this form. Also, you may contact your own doctor, counselor or seek treatment outside of the University of Pennsylvania. Bring this document, and tell your doctor/counselor or his/her staff that you are in a research study being conducted at the University of Pennsylvania. Ask them to call the numbers on the first page of this form for information.

If you are injured and/or feel emotional discomfort from being in the study, the appropriate care will be provided without cost to you, but financial compensation is not otherwise available from the University of Pennsylvania. If you are injured and/or feel emotional discomfort while in the study but it is not related to the study, you and your insurance company will be responsible for the costs of that care.

Will I have to pay for anything?

There are no costs associated with participating in the study.

If you do accrue costs in transportation to and from the study site you will be fully reimbursed, including gas money, parking fees, or cab costs.

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Will I be compensated for participating in the study?

To show our appreciation for your time, we will give you $20/hour. If you decide to withdraw from the study before the study is over, your compensation is $20/hour for the full duration of the time you spend with us.

Who can I call with questions, complaints or if I'm concerned about my rights as a research subject?

If you have questions, concerns or complaints regarding your participation in this research study or if you have any questions about your rights as a research subject, you should speak with the Principal Investigator (Dr. Coslett) listed on page one of this form. If a member of the research team cannot be reached or you want to talk to someone other than those working on the study, you may contact the Office of Regulatory Affairs with any question, concerns or complaints at the University of Pennsylvania by calling (215) 898-2614.

When you sign this document, you are agreeing to take part in this research study. If you have any questions or there is something you do not understand, please ask. You will receive a copy of this consent document.

Signature of Subject: ________________________________

Print Name of Subject: ________________________________

Date: ________________________________

Signature of Person Obtaining Consent: ________________________________

Name of Person Obtaining Consent: ________________________________

Date: ________________________________