RESEARCH ARTICLE

Language and Memory Improvements following tDCS of Left Lateral Prefrontal Cortex

Erika K. Hussey1,3*, Nathan Ward3, Kiel Christianson2,3, Arthur F. Kramer1,3

1 Department of Psychology, University of Illinois at Urbana-Champaign, Champaign, Illinois, United States of America, 2 Department of Education Psychology, University of Illinois at Urbana-Champaign, Champaign, Illinois, United States of America, 3 Beckman Institute for Advanced Science and Technology, University of Illinois at Urbana-Champaign, Urbana, Illinois, United States of America

* ehussey@illinois.edu

Abstract

Recent research demonstrates that performance on executive-control measures can be enhanced through brain stimulation of lateral prefrontal regions. Separate psycholinguistic work emphasizes the importance of left lateral prefrontal cortex executive-control resources during sentence processing, especially when readers must override early, incorrect interpretations when faced with temporary ambiguity. Using transcranial direct current stimulation, we tested whether stimulation of left lateral prefrontal cortex had discriminate effects on language and memory conditions that rely on executive-control (versus cases with minimal executive-control demands, even in the face of task difficulty). Participants were randomly assigned to receive Anodal, Cathodal, or Sham stimulation of left lateral prefrontal cortex while they (1) processed ambiguous and unambiguous sentences in a word-by-word self-paced reading task and (2) performed an n-back memory task that, on some trials, contained interference lure items reputed to require executive-control. Across both tasks, we parametrically manipulated executive-control demands and task difficulty. Our results revealed that the Anodal group outperformed the remaining groups on (1) the sentence processing conditions requiring executive-control, and (2) only the most complex n-back conditions, regardless of executive-control demands. Together, these findings add to the mounting evidence for the selective causal role of left lateral prefrontal cortex for executive-control tasks in the language domain. Moreover, we provide the first evidence suggesting that brain stimulation is a promising method to mitigate processing demands encountered during online sentence processing.

Introduction

Almost all daily mental activities require some form of computational filtering to make sense of noisy input. Executive-control supports these efforts for higher-level cognitive tasks when we must resolve among multiple interfering sources of information. Specifically, it services the
selection of goal-compatible information, allowing us to ignore irrelevant information, including default responses and input that we are biased to automatically process [1–3]. Consider, for example, the task of interpreting speech during a conversation. Listeners must quickly derive meaning from utterances by relying largely on stored linguistic and mnemonic knowledge. Searching this vast information space and integrating it with real-time input (a process referred to as incrementality; see [4]) often gives rise to situations when several eligible meanings exist. A comprehender’s ability to select among conflicting options is crucial for successful communication and relies largely on non-linguistic abilities, like executive-control [5–11]. Here, we focus primarily on executive-control for language use and ask whether using brain stimulation to target a cortical region reputed to support executive-control has concomitant effects on interpretation processes, namely when readers must choose among multiple possible meanings of a sentence.

Converging evidence from neuropsychological patients and neuroimaging in healthy adults indicates a supportive role of left lateral prefrontal cortex (LPFC) in executive-control conditions on tasks in the memory and language domains [12–16]. Patients with focal lesions to left LPFC demonstrate deficits limited to language processing and recognition memory scenarios requiring irrelevant information to be ignored [9,17–19]. In sentence processing, for example, left LPFC patients struggle to correctly arrive at the intended meaning of ambiguous sentences due to their inability to engage executive-control to ignore one (incorrect) interpretation in favor of another (correct) one [9]. Remarkably, sentences without temporary conflict or ambiguity are processed and comprehended with little issue, even when they contain complex syntax that requires additional processing [20], but see [21–22]. The selective nature of these findings extend to the memory domain, such that left LPFC patients consistently show exaggerated effects for familiar-but-irrelevant recognition probes in a recognition memory task, while probes with minimal interference do not suffer [23–24]. Additionally, two new functional neuroimaging findings in healthy adults provide compelling correlational evidence linking left LPFC to executive-control conditions in the memory and language domains. In one instance [25], neural activation during the Stroop task (when a color word is in conflict with its font color) correlated with activation levels in the same participants associated with processing ambiguous sentences like “Clean the frog with the leaf,” where “leaf” can be an instrument (use the leaf to clean the frog) or a modifier (clean the frog that has a leaf). In another study [26], co-localization of activity in left LPFC appeared for the Stroop task, the Flanker task (target arrow direction is in conflict with distractor arrows), and reading Chinese sentences that elicited temporary ambiguity among meanings. Alongside the patient results, co-recruitment patterns indicate that left LPFC subserves a variety of memory and language tasks, suggesting a shared, process-specific role of executive-control across both domains [8–9].

One implication that follows from these findings involves improving language use through interventions that target executive-control. Indeed, preliminary evidence indicates that practice on executive-control tasks leads to improvements on untrained measures of syntactic ambiguity resolution [27–28]. Following multiple weeks of exposure to a performance-adaptive n-back task containing interference lures, trainees were faster to read and more accurate to comprehend syntactically ambiguous sentences. Importantly, other untrained task conditions with minimal executive-control demands did not result in the same improvements after training, and other training groups (that trained on tasks unrelated to executive-control) demonstrated no improvements. Given that the training task (n-back-with-lures) and the improved transfer measure (syntactic ambiguity resolution) recruit left LPFC, it is possible that training honed left LPFC resources, which cascaded into benefits for untrained tasks relying on the same cognitive mechanisms (for similar shared-resource/process-specific arguments, see [27–31]).
To further probe this possibility, we use a non-invasive brain stimulation approach to change cortical excitability in left LPFC and assess the behavioral consequences on syntactic ambiguity resolution and performance on the \( n \)-back task. If \( n \)-back-with-lures and syntactic ambiguity resolution tap the same cognitive mechanism, and if that mechanism is supported in part by left LPFC regions (as the evidence reviewed above suggests), then we would expect tDCS over left LPFC to influence only conditions with elevated executive-control demands in each task. That is, in the present study, we entertain the possibility that tDCS may be a method for testing linking hypotheses between training and transfer measures for future intervention studies that are guided by process-specific principles [29]. In the next section, we describe our brain stimulation method and highlight relevant tDCS findings that delineate the functional role of left LPFC for a range of executive-control measures. We argue that tDCS is a promising tool to assess the causal role of left LPFC-mediated executive-control for language.

**Brain Stimulation of Executive-Control Regions**

There has been a recent influx of studies aimed at temporarily affecting cognition with non-invasive brain stimulation. Here, we focus on transcranial direct current stimulation, or tDCS, a technique that involves sending a small electrical current (1–2 milliamperes, mA) through the scalp from an anode to a cathode with the goal of altering neuronal excitability. Specifically, cortical regions near the anode have shown increased activity due to temporary neuronal depolarization, while regions close to the cathode have shown reduced activity due to acute neuronal hyperpolarization [32–34]. Typically stimulation is accomplished by passing current through two saline-soaked sponges that vary in size from 11cm\(^2\) to 35cm\(^2\) in size; the current study implemented a "high definition" approach by administering the current with two 1.3cm\(^2\) EEG-like electrodes, which has been shown to increase precision and decrease current shunting [35–36].

While not completely ubiquitous [37–39], the facilitatory effects of anodal tDCS have been demonstrated across a variety of cognitive processes [40], including visual perception [41], attention [42], executive function [43–45], learning [46–47], problem solving and planning [48–49], and recognition [50–53]. Relevant for the current study, anodal tDCS has produced several instances of improvement on tasks tapping executive-control. For example, participants show smaller interference effects on the Stroop task following anodal stimulation over left or right LPFC for 20 minutes compared to sham controls [54–55]. Similarly, compared to sham stimulation, 10 minutes of anodal stimulation over left LPFC resulted in faster responses on a recent-negatives Sternberg recognition memory task [56]. Finally, Ohn and colleagues compared sham stimulation to anodal tDCS over left LPFC and found higher accuracy on a 3-back task [57]. Pertinent to the latter effect, a recent review of tDCS and \( n \)-back studies reported improved performance across 33 experiments for anodal tDCS over prefrontal regions compared to sham stimulation [58]. To evaluate the role of left LPFC for executive-control demands in \( n \)-back, we included a modified version of the \( n \)-back task containing interference lures [59–60].

In addition to the executive-control benefits of anodal stimulation over LPFC in the memory domain, there are also many reports of tDCS-mediated improvements in language processing, including artificial grammar learning [61], verbal categorization [62], reading efficiency [63], and language production among healthy adults and individuals with aphasia [64]. Many of these findings involve stimulating temporal regions, but those involving stimulation of left LPFC generally result in quicker production times to picture cues [65–68], better semantic fluency [69–71], faster proper naming [72], and fewer speech errors [73–74]. Such production-based facilitation effects are accompanied by decreased left LPFC activation [68], increased
functional connectivity within the default mode network [72], and reduced activity in the delta frequency band [75] (see [76] for complementary evidence in the alpha band for the n-back task). These findings suggest that the improved mechanism may be inhibitory in nature (i.e., a component of executive-control) [74].

Alongside the converging evidence for the role of left LPFC for executive-control, and in light of the extant evidence for tDCS-mediated improvement in executive-control and language processing, we anticipate anodal stimulation of left LPFC to positively influence sentence comprehension and real-time interpretation efforts when readers must resolve syntactic ambiguity. Promising relevant psycholinguistic data exist for sentence production [73] and idiom comprehension [77] such that both tasks benefit from acute left LPFC stimulation. To our knowledge, however, the present study constitutes the first effort to test for the effects of left prefrontal tDCS in the sentence comprehension domain.

Materials and Methods

Participants

Seventy-nine participants were assigned to receive anodal, cathodal, or sham tDCS over left LPFC. Twenty-seven participants received anodal stimulation (12 females; M: 19.5 years; range: 18–23 years), 26 received cathodal stimulation (11 females; M: 20.2 years; range: 18–28 years), and 26 received sham (12 females; M: 20 years; range: 18–25 years). Stimulation was administered in a single-blind design, such that participants were unaware of their group assignment. All participants reported being right-hand dominant, fluent English speakers, and no one had any prior experience with tDCS.

Design

Following tDCS electrode application, all participants completed two behavioral tasks in the language (Reading Task) and memory (N-Back Task) domains (see Fig 1). All participants completed the reading task first (time-on-task M = 29m, SD = 6.3m, range: 18–42m) followed by the n-back task (time-on-task M = 28m, SD = 3.7m, range: 16–40m). The stimulation period began at the onset of the reading task and lasted for 30 minutes. Because the tasks were self-paced, subjects received different amounts of simultaneous (or “online”) stimulation while performing the tasks. More than half of the subjects (n = 51) experienced stimulation for the entirety of the reading task, with 38 of these participants also receiving stimulation during the n-back task. Importantly, given that the effects of tDCS can persist for up to 90 minutes beyond active stimulation episodes [32,78], the stimulation was expected to modulate performance on both tasks. All participants finished the study by filling out a questionnaire that assessed expectations of stimulation group assignment and other experiences throughout the session.

tDCS Protocol

Two high-definition electrodes were placed on the left side of the head to send a current through only the left hemisphere, targeting left LPFC. The polarity of the current minimally differed in the Anodal and Cathodal groups, such that the anode was placed over left LPFC (cathode over left occipital cortex) for participants in the Anodal group and the anode over left occipital cortex (cathode over left LPFC) for those in the Cathodal group. Participants assigned to receive sham stimulation always had an anode over left LPFC and cathode over left occipital cortex.

Apparatus. Stimulation was delivered via a Soterix Medical 1x1 Transcranial Direct Current Low-Intensity Stimulator (Model 1300A). Anode and cathode cables were connected to
the device and 1.3 cm$^2$ high-definition Ag/AgCl electrodes [79] were attached. Modular electroencephalogram caps manufactured by EasyCap were outfitted with electrode holders over sites F3 and O1 according to international 10–20 standards [80] into which the electrodes were placed for stimulation.

We analyzed the local electric field generated through the brain with 3D finite element modeling as a function of our selected electrode sites using the COMETS toolbox for MATLAB [81]. Fig 2 shows the estimated cortical stimulation current for the anodal and cathodal groups based on a standard Montreal Neurological Institute (MNI) human head model. The change in cortical excitability between the two montages demonstrates that there is minimal bridging between electrodes such that stimulation is primarily restricted to left lateral prefrontal and left occipital regions.

**Procedure.** The University of Illinois, Urbana-Champaign Institutional Review Board approved all procedures used. All participants signed an informed consent document and were told that the study involved “high-definition” electrode montages to precisely target brain regions by sending a weak current through two small electrodes on the left side of the head. All participants’ head circumferences were measured from the inion to the nasion to select the appropriate cap size. The electrode cap was positioned such that front and back midline edges of the cap were 1 centimeter from the inion and 3 centimeters from the nasion, respectively. Electrode sites were prepared with highly conductive gel (SignaGel, Parker Laboratories, Fairfield, NJ), and electrodes were attached to the tDCS device.

Participants in the Anodal and Cathodal stimulation groups received 2.0 mA current for a full 30-minute period. Stimulation was ramped up and ramped down over 30 seconds at the beginning and end of each session, with continuous current applied for 30 minutes. Participants in the Sham group underwent all of the same procedures as those in the Anodal and
Cathodal groups except that the current lasted only 30 seconds at the start and end of the session. The comparable ramp-up/ramp-down sequence for Sham controls elicits the same sensation to equalize expectations about whether stimulation was applied, but does not induce any substantial neuronal effects [82–83]. All participants experienced a short exposure period to acclimate to the stimulation sensation before the longer stimulation period began, and no participants reported any discomfort or pain throughout the session.

**Reading Task**

To assess the selective role of left LPFC-mediated executive-control for sentence processing, participants read syntactically ambiguous and unambiguous sentences (Sentences 1 and 2 in Table 1), embedded among object- and subject-extracted relative clause sentences (Sentences 3 and 4 in Table 1; see S1 Table for all stimulus sentences). Ambiguous sentences like 1a and 1b invoke executive-control due to their temporary ambiguity [8]. Specifically, the verb "hid" can
be used transitively (the thief is hiding the jewelry) or reflexively (the thief is hiding himself). Although the correct analysis of this sentence is unknown until late arriving information appears that signals the reflexive interpretation (“sparkled brightly”), native English readers strongly prefer a transitive interpretation initially, because “jewelry” is a semantically viable object that thieves might hide [84–86]. That is, on-the-fly sentence processing lures readers down the “garden-path” to expect one interpretation (the transitive), when in fact, another is ultimately revealed to be correct (the reflexive). Executive-control supports such syntactic ambiguity resolution by allowing readers to inhibit their initial preferred transitive interpretation in favor of the correct reflexive meaning [27,87–89]. Sentences like 2a and 2b in Table 1 reverse the clause order, removing any temporary ambiguity, and thus, the need to use executive-control to resolve among interpretations is diminished.

Interestingly, elongating the ambiguous portion of the sentence (prior to the disambiguating information, “sparkled brightly”) gives rise to larger garden-path effects, due to a mounting incremental processing commitment [84] (Sentence 1b in Table 1). Within the context of a word-by-word self-paced moving-window reading paradigm (see description below), elongating the ambiguous sentence region also places a premium on other cognitive demands, like working memory [90]. As a result, this manipulation introduces task-level complexity that may be separable from the executive-control demands encountered in ambiguous sentences. Thus, if active stimulation of left LPFC influences executive-control alone, the Anodal group should outperform the Cathodal and Sham groups only on ambiguous items, regardless of sentence length prior to the introduction of disambiguating information (at “sparkled brightly”).

To further test the selectivity of executive-control in sentence processing, we also included relative clause sentences, which incur processing costs due to cognitive demands largely separable from executive-control [91]. Specifically, reading times in the embedded relative clause region of object-extracted items (the bolded section in Sentences 3a and 3b in Table 1, “who the expert questioned”) are typically longer relative to the comparable region in subject-extracted sentences (the bolded section in Sentences 4a and 4b in Table 1, “who questioned the expert”). This increased processing difficulty has been explained in terms of greater syntactic complexity due to integration costs, such that the representation associated with the subject

| Sentence                                                                                                                                                                                                 | Conflict Level       | Difficulty Level   |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|--------------------|
| 1a While the thief /hid /the jewelry that was elegant and expensive /sparkled brightly.                                                                                                                    | High (Ambiguous)     | High (Long)        |
| 1b While the thief /hid/ the jewelry /sparkled brightly.                                                                                                                                                   | High (Ambiguous)     | Low (Short)        |
| 2a The jewelry that was elegant and expensive/ sparkled brightly /while the thief /hid.                                                                                                                   | Low (Unambiguous)    | High (Long)        |
| 2b The jewelry /sparkled brightly /while the thief /hid.                                                                                                                                                 | Low (Unambiguous)    | Low (Short)        |
| 3a The farmer /who the expert questioned that was outgoing and enthusiastic /promoted /the product /at the fair.                                                                                         | Low                  | High (Long OE)     |
| 3b The farmer /who the expert questioned /promoted /the product /at the fair.                                                                                                                           | Low                  | High (Short OE)    |
| 4a The farmer /who questioned the expert that was outgoing and enthusiastic /promoted /the product /at the fair.                                                                                           | Low                  | High (Long SE)     |
| 4b The farmer /who questioned the expert /promoted /the product /at the fair.                                                                                                                           | Low                  | Low (Short SE)     |

Example Garden-Path (1–2) and Relative Clause (3–4) sentences. Slashes indicate sentence region boundaries used for reading time analyses, where bold denote the regions of interest. OE = object-extracted; SE = subject-extracted

doi:10.1371/journal.pone.0141417.t001
noun phrase ("the farmer") may partially decay before a reader encounters the verb ("promoted"; [92–93]). Furthermore, and relevant to the current claim, there is no association between left LPFC and comprehension of syntactically complex sentences like relative clauses among patients with circumscribed damage to this region [94], yet injury to left LPFC reliably predicts failure to recover from garden-path misinterpretations [9,19,87]. Therefore, Anodal stimulation of left LPFC should not influence processing under all states of effortful sentence processing, but rather only when executive-control demands are high (i.e., when one seemingly correct interpretation must be inhibited in favor of another).

**Materials.** Participants read a total of 144 sentences. Twenty-four verbs were used that contained the transitive/reflexive ambiguity and 2 distinct contexts were created for each verb to create a total of 48 unique sentence frames. Four versions of each sentence were created to vary minimally in terms of Conflict Level (ambiguity) and Difficulty Level (length), resulting in 12 sentences for each of the 4 conditions (e.g., Sentences 1a, 1b, 2a, 2b in Table 1). We created 4 lists by Latin-squaring conditions, so as to not include a repeating frame within a list. For example, if List 1 contained a short ambiguous version of a sentence, then List 2 would contain the long ambiguous form, List 3 the short unambiguous sentence, and List 4 the long unambiguous version. Similarly, 48 unique relative clause sentences were used that varied minimally in terms of subject- or object-extraction and length (short or long), resulting in 12 sentences for each of the 4 conditions (e.g., Sentences 3a, 3b, 4a, 4b in Table 1). The same Latin-square approach was applied to these materials, as well, to create 4 sets within each of the 4 lists. We fully counterbalanced list administration across participants to ensure equal numbers of observations for each item. The 96 critical constructions were embedded within 48 additional filler sentences, which did not involve garden-path recovery or relative clause extractions, and contained a range of structures to conceal both manipulations. All items were pseudorandomized within each list to prevent any within-condition repeats on back-to-back trials. An exhaustive list of the critical items (garden-path and relative clause sentences) can be found in the **S1 Table**.

**Procedure.** Participants read sentences via a non-cumulative, self-paced moving-window design; each word was shown one at a time as the subjects pressed a button until all words in a sentence were presented just once [95]. Sentences appeared on a single line with a dash replacing all letters and punctuation, with spaces between words preserved (see Fig 1). As participants pressed buttons, the dashes corresponding to the current word disappeared to reveal that word. Upon pressing the "Next" button, the word was masked with dashes and the following word appeared. Participants were not allowed to revisit words of the sentence after they appeared. Following the final word in the sentence, a yes/no comprehension question appeared on a new screen. For the garden-paths, these questions probed for the reflexive interpretation (e.g., “Did the thief hide himself?” for Sentences 1 and 2 in Table 1); therefore, an incorrect ‘no’ response indexed offline misanalysis and a correct ‘yes’ response indexed successful revision [84,96]. As a result, for all ambiguous and unambiguous sentences, the correct answer was always ‘yes.’ For the relative clauses, the questions gauged comprehension of information unrelated to the embedded clause interpretation (e.g., ”Was the product promoted on TV?” for Sentences 3 and 4 in Table 1). Across all items in a list, yes/no responses were equally likely. We recorded accuracy to comprehension questions and word-by-word response times on each trial for later analysis.

**N-Back Task**

Following the reading task, participants performed an n-back letter memory task during which they indicated when a current item matched an item presented n trials prior. Similar to the
design of the reading task, our version of n-back minimally and parametrically varied Conflict Level and Difficulty Level. Difficulty was manipulated by changing the number of to-be-remembered items (n-level); for example, remembering 2 items back is easier than remembering 4 items back due to changes in processing demands that are distinct from executive-control [97]. Conflict was manipulated by introducing highly-familiar non-target stimuli (interference lures), which are known to engage left LPFC executive-control brain regions [98–100].

Procedure. Following a 500ms fixation cross, letters were displayed serially for 500ms with an ISI of 2s. All letters were drawn from a subset of phonologically distinct consonants (b, c, d, f, h, j, k, l, m, p, q, r, s, t, v, x) and were displayed in mixed upper- and lower-case to prevent participants from responding simply based on iconic memory. Participants indicated by button press whether the current letter, regardless of case, had appeared n items previously by pressing one of two keys corresponding to ‘Target’ or ‘Non-Target.’ Participants performed two blocks of 2-back followed by 2 blocks of 4-back. All sequences contained 20+n items, partitioned into 6 targets and 14+n fillers. The second half of the blocks at each n-level contained 6 interference lures and 8+n fillers. Lures were defined as items that repeated in positions n+1, n+2, n-1, and n-2 [28,60]. For example, during a 2-back task, the second appearance of J in the sequence j, p, k, j is considered a lure because it matches the identity of an item presented 3 trials prior instead of 2 trials prior (see Fig 1). All participants began the task with a practice 2-back sequence, followed by blocks of n-back in ascending difficulty: 2-back-without-lures, 2-back-with-lures, 4-back-without-lures, and 4-back-with-lures. Feedback in terms of accuracy and average response time was provided after each sequence. All participants performed five sequences of each block, and they were explicitly notified when the task transitioned from 2-back to 4-back, but not notified when lures were introduced at each n-level. We recorded accuracy and response time for each item in a sequence, as well as accuracy on entire sequences for later analysis.

Results

Statistical Analysis

Linear mixed-effects models (using R’s lme4.0 package version 1.17) were used to evaluate reading and n-back performance. We included Stimulation (anodal, cathodal, sham), Conflict Level (high, low), and Difficulty Level (high, low) as fixed (independent) factors in all of our models. We also included random effects of Subjects and nested random slopes for the fixed factors to account for participant variability to stimulation, conflict, and difficulty. For the reading measures, we also included a random intercept term for Items and nested random slopes of the fixed factors to account for item-level variability in conflict and difficulty [101]. For each dependent measure, we selected the maximal model that converged (i.e., the model containing the most allowable slope terms [102]). In all of the model summary tables, we report model coefficients, standard errors, and t- or z-values for each main effect and higher-level interaction. P-values were determined using a Kenward-Roger approximation [103]. When discussing each model below, we first describe task-level effects (i.e., main effects of Difficulty and Conflict and the interaction between Difficulty and Conflict), followed by any Stimulation effects. Each subject’s data are provided in S1 File.

Contrast coding. Within-subjects fixed factors (Conflict Level and Difficulty Level) were assessed via mean-centered orthogonal Helmert coding, which allowed us to examine the difference between factor levels while accounting for differences in the number of observations contributing to each factor level [104]. Contrast coding was determined on the basis of hypothesized effects: Positive values were assigned to factor levels expected to elicit worse performance. For example, because we expected 4-back to lead to worse performance than 2-back,
Difficulty Level in the N-Back Task would be coded with a positive coefficient for 4-back (0.5) and a negative for 2-back (-0.5). Thus, a positive model coefficient for the main effect of N-Back Difficulty Level would signal worse performance on 4-back relative to 2-back, while a negative coefficient would suggest worse 2-back performance relative to 4-back. With respect to the remaining factors, we positively coded the following levels: lures of N-Back Conflict Level, ambiguous of Garden-Path Conflict Level, long of Garden-Path Difficulty Level, object-extracted of Relative Clause Sentence Type, and long of Relative Clause Difficulty Level. For more information on comprehensively interpreting effects on the basis of model coefficients, see [105].

To test for the effects of Stimulation, we implemented two models with dummy contrast coding that varied only in their baseline reference level. In this case, the reference level was compared to the remaining levels. For instance, the first model included the Anodal group as the reference level, which allowed us to compare Anodal vs. Sham and Anodal vs. Cathodal. Since Cathodal and Sham stimulation are not compared to one another in this contrast, we implemented a second contrast coding with the Sham group as the reference level, which gave us coefficients comparing Sham vs. Anodal and Sham vs. Cathodal. Combining two contrast codes allowed us to make comparisons of each group with every other group [106]. Since both contrasts share one redundant comparison (Anodal vs. Sham), we report only the model coefficients for this comparison from the first contrast (with Anodal as the reference level).

We expect effects for all three comparisons if Anodal stimulation of left LPFC improves executive-control and Cathodal stimulation compromises performance, such that Anodal stimulation should result in superior performance relative to the Sham and Cathodal stimulation, and the Sham group should outperform the Cathodal group. Moreover, if stimulating left LPFC has selective effects on executive-control, then we would only expect Stimulation to interact with Conflict Level (and not Difficulty Level). If Stimulation interacts with only Difficulty Level, this would indicate that left LPFC services cases of heightened difficulty, regardless of the need for executive-control; whereas, if Stimulation interacts with both Conflict Level and Difficulty Level, we would conclude that left LPFC supports both processing demands.

Reading Performance

Reinterpretation abilities were assessed via comprehension accuracy and reading time. For both measures in garden-path sentences, we assessed Conflict Level (high: ambiguous sentences; low: unambiguous sentences) and Difficulty Level (high: long sentences; low: short sentences). For relative clauses, we assessed Difficulty Level with sentence type (high: object-extracted sentences; low: subject-extracted) and sentence length (high: long sentences; low: short sentences).

Garden-path comprehension accuracy. Comprehension accuracy was modeled as a binomial variable using a generalized linear mixed-effects model (Table 2). Replicating prior garden-path findings [84, 85], we observed a main effect of Conflict Level and an interaction of Conflict Level and Difficulty Level (see Fig 3). Specifically, ambiguous sentences resulted in worse accuracy compared to unambiguous items (MA = 0.741 vs. MU = 0.924), an effect that was exaggerated in longer sentences (MA = 0.632 vs. MU = 0.923) compared to shorter ones (MA = 0.849 vs. MU = 0.925). We also observed a main effect of Difficulty Level, indicating that longer sentences resulted in worse average accuracy than shorter sentences (ML = 0.777 vs. MS = 0.887).

Interestingly, in terms of stimulation effects, the models revealed a significant interaction between Conflict Level and Stimulation for just the anodal/cathodal contrast. As predicted, the Anodal group demonstrated overall better accuracy on ambiguous items compared to the
Cathodal group (MAnodal = 0.778 vs. MCathodal = 0.715). No effects emerged for the remaining contrasts, though the effect was numerically in the direction that polarity effects would predict; the Anodal group was more accurate on ambiguous items than the Sham group (MSham = 0.728), which was more accurate than the Cathodal group. We did not find a three-way interaction of Difficulty Level, Conflict Level, and Stimulation; a two-way interaction of Difficulty Level and Stimulation; or a main effect of Stimulation for any contrasts.

Garden-path reading time. We examined the real-time processing effects of garden-path recovery by measuring button presses to individual words as participants read sentences. We removed trials with incorrect responses to comprehension questions (loss of 16.7% of trials) in order to examine cases when garden-path recovery was successful, or when readers correctly revised an initial misinterpretation. Of the correct trials, we then removed button press times that were less than 200ms and greater than 2000ms (loss of 3.04% of words). The remaining raw word-by-word button presses were summed to create four a priori regions of interest (as delimited by slashes in Table 1). The final region of ambiguous sentences contains the disambiguating information (“sparkled brightly”), which is where we would expect to find any effects related reanalysis—namely, those mediated by executive-control [107–108].

Table 2. Estimate coefficients from generalized linear mixed-effects models for garden-path accuracy on the reading task.

| Predictor | Coefficient | SE  | z-value |
|-----------|-------------|-----|---------|
| Intercept | 2.589       | 0.267 | 9.686*  |
| Conflict Level | 1.526 | 0.316 | 4.826*  |
| Difficulty Level | 0.841 | 0.247 | 3.409*  |
| Conflict Level x Difficulty Level | -1.227 | 0.456 | -2.694* |
| Anodal vs. Cathodal | -0.038 | 0.312 | -0.123 |
| Anodal vs. Sham | -0.219 | 0.308 | -0.711 |
| Sham vs. Cathodal | 0.203 | 0.317 | 0.639 |
| Conflict Level x Anodal/Cathodal | 0.925 | 0.378 | 2.449*  |
| Conflict Level x Anodal/Sham | 0.459 | 0.367 | 1.251 |
| Conflict Level x Sham/Cathodal | 0.309 | 0.363 | 0.850 |
| Difficulty Level x Anodal/Cathodal | 0.045 | 0.335 | 0.133 |
| Difficulty Level x Anodal/Sham | -0.002 | 0.323 | -0.006 |
| Difficulty Level x Sham/Cathodal | 0.049 | 0.338 | 0.146 |
| Conflict Level x Difficulty Level x Anodal/Cathodal | -0.521 | 0.609 | -0.856 |
| Conflict Level x Difficulty Level x Anodal/Sham | 0.121 | 0.579 | 0.209 |
| Conflict Level x Difficulty Level x Sham/Cathodal | -0.568 | 0.608 | -0.934 |

Random Effects

| Subjects (Intercept) | 0.9374 |
| Subjects (Conflict Level) | 0.6324 |
| Subjects (Difficulty Level) | 0.2587 |
| Subjects (Conflict Level x Difficulty Level) | 0.0045 |
| Items (Intercept) | 0.9154 |
| Items (Conflict Level) | 0.5032 |

Difficulty Level refers to the length of the ambiguous region (long vs. short) and Conflict Level refers to sentence ambiguity (ambiguous vs. unambiguous). Bold indicates coefficients that are significant.

SE = standard error

*significant at the p<0.05 level

doi:10.1371/journal.pone.0141417.t002

Cathodal group (MAnodal = 0.778 vs. MCathodal = 0.715). No effects emerged for the remaining contrasts, though the effect was numerically in the direction that polarity effects would predict; the Anodal group was more accurate on ambiguous items than the Sham group (MSham = 0.728), which was more accurate than the Cathodal group. We did not find a three-way interaction of Difficulty Level, Conflict Level, and Stimulation; a two-way interaction of Difficulty Level and Stimulation; or a main effect of Stimulation for any contrasts.

Garden-path reading time. We examined the real-time processing effects of garden-path recovery by measuring button presses to individual words as participants read sentences. We removed trials with incorrect responses to comprehension questions (loss of 16.7% of trials) in order to examine cases when garden-path recovery was successful, or when readers correctly revised an initial misinterpretation. Of the correct trials, we then removed button press times that were less than 200ms and greater than 2000ms (loss of 3.04% of words). The remaining raw word-by-word button presses were summed to create four a priori regions of interest (as delimited by slashes in Table 1). The final region of ambiguous sentences contains the disambiguating information (“sparkled brightly”), which is where we would expect to find any effects related reanalysis—namely, those mediated by executive-control [107–108]. We present
mixed-models only for reading times in this final region. Note that due to the reversed clause order of control sentences, this region contains different content in the unambiguous items (e.g., “hid”). We justified using the sentence-final region as our comparison to control for “wrap-up effects” (see also [28]). Finally, because sentence regions often varied in string length (and length is a highly reliable predictor of sentence reading time), all mixed-models also included a covariate of region string length in terms of number of characters (see [109] for additional rationale).

Table 3 includes the model estimates of reading times in Region 4. Although there was no main effect of Difficulty Level, we observed a significant main effect of Conflict Level, alongside an interaction between Conflict Level and Difficulty Level. Ambiguous final regions were read more slowly than unambiguous final regions (MAM = 1036ms vs. MUN = 411ms, uncorrected; see Fig 4). Moreover, the conflict effect (Ambiguous–Unambiguous performance) was larger for Long sentences compared to short ones (MLong = 666 ms vs. MShort = 558ms, uncorrected).

Although there was no main effect of Stimulation, we observed an interaction of Difficulty Level and Stimulation for the Anodal/Sham contrast, such that the Anodal group was faster to read long sentences compared to the Sham group (MAnodal = 793ms vs. MSham = 870ms, uncorrected). The Cathodal group did not differ from any other group when reading long sentences.

**Fig 3. Garden-path comprehension accuracy.** Average comprehension accuracy to questions following garden-path sentences for each stimulation group and task condition. Error bars = ±1 standard error of the mean.
doi:10.1371/journal.pone.0141417.g003
but was numerically slower than the Sham group, as expected ($M_{\text{Cathodal}} = 901\text{ms}$). No effects appeared for the remaining sentence regions ($t_s<0.91, p_s>0.36$). We also did not observe any interactions of Conflict Level and Stimulation or any interactions of Difficulty Level, Conflict Level, and Stimulation for the contrasts.

Considering both measures of garden-path recovery, we provide initial evidence that acute brain stimulation to left LPFC can influence sentence processing in real-time reanalysis and offline comprehension accuracy. Left LPFC seems to service both conflict and difficulty demands within garden-path recovery. Sentence reading time measures show positive effects of Anodal stimulation in the sentence-final region for only long sentences, regardless of syntactic ambiguity. Later comprehension accuracy is best for the Anodal stimulation group on only ambiguous sentences with heightened executive-control demands, regardless of sentence length.

Table 3. Estimate coefficients from linear mixed-effects models for reading times in the critical area of garden-path sentences.

| Predictor                                      | Coefficient | SE    | t-value |
|------------------------------------------------|-------------|-------|---------|
| Fixed Effects                                  |             |       |         |
| Intercept                                      | 375.654     | 47.873| 7.847*  |
| Region Length (covariate)                      | 42.886      | 3.609 | 11.885* |
| Conflict Level                                 | -270.012    | 43.070| -6.269* |
| Difficulty Level                               | 5.203       | 26.337| 0.198   |
| Conflict Level x Difficulty Level              | -109.195    | 53.975| -2.023* |
| Anodal vs. Cathodal                            | 41.874      | 47.571| 0.880   |
| Anodal vs. Sham                                | 22.178      | 47.581| 0.466   |
| Sham vs. Cathodal                              | 19.291      | 48.021| 0.402   |
| Conflict Level x Anodal/Cathodal               | -67.973     | 41.556| -1.636  |
| Conflict Level x Anodal/Sham                   | -17.775     | 41.518| -0.428  |
| Conflict Level x Sham/Cathodal                 | -50.207     | 42.953| -1.169  |
| Difficulty Level x Anodal/Cathodal             | 17.106      | 26.400| 0.648   |
| Difficulty Level x Anodal/Sham                 | 56.049      | 26.386| 2.124*  |
| Difficulty Level x Sham/Cathodal               | -38.680     | 27.211| -1.421  |
| Conflict Level x Difficulty Level x Anodal/Cathodal| -31.638   | 57.410| -0.551  |
| Conflict Level x Difficulty Level x Anodal/Sham| -76.467    | 57.299| -1.335  |
| Conflict Level x Difficulty Level x Sham/Cathodal| 42.734     | 58.987| 0.470   |

Random Effects

| Predictor                                      |        |       |        |
|------------------------------------------------|--------|-------|--------|
| Subjects (Intercept)                           | 27693  |       |        |
| Subjects (Conflict Level)                      | 13706  |       |        |
| Subjects (Difficulty Level)                    | 156    |       |        |
| Subjects (Conflict Level x Difficulty Level)   | 6830   |       |        |
| Items (Intercept)                              | 9471   |       |        |
| Items (Conflict Level)                         | 30988  |       |        |
| Items (Difficulty Level)                       | 16355  |       |        |
| Items (Conflict Level x Difficulty Level)      | 61123  |       |        |
| Residuals                                      | 89428  |       |        |

The critical region (Region 4) is “sparkled brightly” in ambiguous sentences and “hid” in unambiguous sentences. Difficulty Level refers to the length of the sentence (long vs. short) and Conflict Level refers to sentence ambiguity (ambiguous vs. unambiguous). Bold indicates coefficients that are significant.

SE = standard error

*significant at the $p<0.05$ level

doi:10.1371/journal.pone.0141417.t003
Relative clause reading time. In addition to garden-path sentences, participants read relative clause sentences. These items were included as controls to examine the real-time processing effects on constructions containing linguistic complexities linked to other general-purpose cognitive abilities aside from executive-control (i.e., working memory, linguistic integration, and retrieval demands). We predicted no effects in the critical embedded clause region of these items if stimulation of left LPFC selectively influences executive-control. If the Difficulty Level-by-Stimulation effects reported above for garden-path reading times were due to task complexity alone, then other cases of complexity should show comparable results. Namely, we would expect to also see effects of relative clause Sentence Type (object-extracted are more demanding the subject-extracted clauses) and Sentence Length (longer sentences should be more difficult to process compared to shorter items).

We used a similar data processing pipeline from the garden-path sentences for the relative clause reading times. Incorrect trials were removed (loss of 16.5% of trials), as well as button press times that were less than 200ms and greater than 2000ms (loss of 3.65% of words). The remaining word-level button presses were chunked into four regions of interest (see Table 1), with the embedded clause (Region 2) being the critical sentence area. The mixed models of
reading times in this critical region included a covariate of Region Length to control for number of characters. In terms of task-level effects, we observed only a main effect of Difficulty Level, such that longer sentences were read more slowly than short sentences ($M_{\text{Long}} = 3253\text{ms}$ vs. $M_{\text{Short}} = 1814\text{ms}$, uncorrected). The model revealed no effects of Sentence Type and no effects involving Stimulation for any contrasts (Table 4; Fig 5). The lack of any reliable interactions containing Stimulation suggests that active stimulation to left LPFC does not have an effect on difficult sentence processing conditions broadly construed (i.e., when executive-control demands are removed).

**N-Back Performance**

We evaluated the effects of left LPFC stimulation on recognition memory with a modified $n$-back task that parametrically introduced conflict (high: $n$-back-with-lures; low: $n$-back-without-lures) and difficulty demands (high: 4-back; low: 2-back). Performance was assessed with non-parametric signal detection indices of target/non-target discrimination ($A'$) and response criterion ($Grier$'s $B''$ [110]). Measures were computed separately for each subject for each of the 4 task conditions.

Table 4. Estimate coefficients from linear mixed-effects models for length-corrected reading times in the critical region of relative clauses.

| Predictor                        | Coefficient | SE   | t-value |
|----------------------------------|-------------|------|---------|
| Fixed Effects                    |             |      |         |
| Intercept                        | 2110.047    | 239.210 | 8.821*  |
| Region Length (covariate)        | 23.848      | 5.976 | 3.991*  |
| Sentence Type                    | -60.559     | 59.142 | -1.024  |
| Difficulty Level                 | 1561.640    | 181.100 | 8.623*  |
| Sentence Type x Difficulty Level | -10.250     | 114.292 | -0.090  |
| Anodal vs. Cathodal              | 111.545     | 197.297 | 0.565   |
| Anodal vs. Sham                  | 119.027     | 197.283 | 0.603   |
| Sham vs. Cathodal                | -7.482      | 199.158 | -0.038  |
| Sentence Type x Anodal/Cathodal  | -0.016      | 84.547 | 0.000   |
| Sentence Type x Anodal/Sham      | 130.423     | 84.421 | 1.545   |
| Sentence Type x Sham/Cathodal    | -130.440    | 85.393 | -1.528  |
| Difficulty Level x Anodal/Cathodal | 156.660   | 158.414 | 0.989   |
| Difficulty Level x Anodal/Sham   | 99.593      | 158.272 | 0.629   |
| Difficulty Level x Sham/Cathodal | 57.067      | 159.889 | 0.357   |
| Sentence Type x Difficulty Level x Anodal/Cathodal | -23.375 | 163.493 | -0.143  |
| Sentence Type x Difficulty Level x Anodal/Sham | 52.945 | 163.158 | 0.324   |
| Sentence Type x Difficulty Level x Sham/Cathodal | -76.319 | 165.118 | -0.462  |

Random Effects

| Predictor                        | Coefficient | SE   |
|----------------------------------|-------------|------|
| Subjects (Intercept)             | 499255      |      |
| Subjects (Difficulty Level)      | 267024      |      |
| Subjects (Sentence Type)         | 29515       |      |
| Subjects (Sentence Type x Difficulty Level) | 93252 |      |
| Items (Intercept)                | 8639        |      |
| Items (Difficulty Level)         | 14575       |      |
| Residuals                        | 634184      |      |

Region 2 is the critical sentence region. For relative clauses, Difficulty Level refers to the length of the embedded clause region (long vs. short) and Sentence Type refers to extraction (object-extracted vs. subject-extracted). Bold indicates coefficients that are significant. SE = standard error

*significant at the p<0.05 level

doi:10.1371/journal.pone.0141417.t004
Discrimination (A’). In terms of task-level effects, the model of A’ did not reveal a significant interaction between Difficulty Level and Conflict Level or a main effect of Conflict Level. We did, however, observe a marginal main effect of Difficulty Level, such that all participants were numerically better able to discriminate targets from non-targets on 2-back blocks compared to 4-back blocks (M_{2\text{Back}} = 0.880 vs. M_{4\text{Back}} = 0.786; Table 5 and Fig 6).

With regard to stimulation effects, we found a reliable interaction of Difficulty Level and Stimulation. The Anodal group outperformed the Cathodal and Sham groups in terms of discriminability on more difficult n-back sequences (4-back), regardless of the presence of interference lures. Indeed, the Anodal group demonstrated better discriminability (i.e., larger A’ values) relative to the remaining groups on the 4-back blocks (M_{\text{Anodal}} = 0.813, M_{\text{Cathodal}} = 0.785, M_{\text{Sham}} = 0.758), but not on the 2-back blocks (M_{\text{Anodal}} = 0.859, M_{\text{Cathodal}} = 0.904, M_{\text{Sham}} = 0.878). The difference between the Sham and Cathodal did not reach significance. In addition, the model revealed a reliable interaction of Conflict Level and Stimulation, such that the Anodal group outperformed the Cathodal group in terms of target/non-target discrimination on n-back blocks with lures (M_{\text{Anodal}} = 0.840, M_{\text{Cathodal}} = 0.832), but that the opposite was
true for $n$-back blocks without lures ($M_{Anodal} = 0.832$, $M_{Cathodal} = 0.857$). Put differently, the Cathodal group shows more of a decline in performance for blocks with lures, a deficit that active stimulation over left LPFC may have protected subjects against in the Anodal group. Despite this, the model did not show the same interaction for the anodal/sham contrast. We also did not find a main effect of Stimulation or a reliable 3-way interaction of Difficulty Level, Conflict Level, and Stimulation for any of the group comparisons.

Response criterion (Grier’s $B'$). The mixed-effects model of Grier’s $B'$ resulted in several task-level effects. Specifically, we observed significant main effects of Difficulty Level, Conflict Level, and an interaction of these two factors (Table 6). Participants were more conservative on 4-back relative to 2-back blocks ($M_{4Back} = 0.251$ vs. $M_{2Back} = 0.132$) and on $n$-back-without-lures compared to cases with lures ($M_{NoLures} = 0.254$ vs. $M_{Lures} = 0.129$; see Fig 7). Interestingly, the interaction between Difficulty Level and Conflict Level was driven by the lowest (least conservative) response criterion on the 2-back-with-lures block ($M = 0.042$ vs. all other $M$‘s $> 0.216$). Perhaps, this is because the 2-back-with-lures block was participants’ first exposure to lure items, which may have resulted in more ‘yes’ responses than normal.

Considering stimulation-based effects, we found a significant three-way interaction of Difficulty Level, Conflict Level, and Stimulation for the cathodal/sham and cathodal/anodal contrasts. These interactions are due to large differences between the Cathodal group and the remaining groups on 2-back-without-lures and 4-back-with-lures (difference of 0.176 vs.
0.135, respectively), but not on 2-back-with-lures and 4-back-without-lures (difference of 0.091 vs. 0.088). Despite this, we found no two-way interactions of Conflict Level and Stimulation or Difficulty Level and Stimulation for any contrasts. We did, however, note a significant main effect of Stimulation group, indicating that the Cathodal group demonstrated a higher likelihood of responding ‘non-target’ (i.e., higher Grier’s $B''$ values, or a more conservative response criterion) compared to the Anodal and Sham groups, in general ($M_{Anodal} = 0.147$, $M_{Sham} = 0.151$; $M_{Cathodal} = 0.259$).

These $n$-back results indicate that Anodal stimulation over left LPFC gives rise to performance boosts in terms of $n$-back discriminability on cases of heightened conflict and difficulty (i.e., both when lures are introduced and when $n$-level is high), but not in terms of response criterion.

**Discussion**

We demonstrated that participants who received Anodal stimulation of left LPFC outperformed those assigned to receive Cathodal or Sham stimulation on most task conditions requiring executive-control in the memory and language domains. Fig 8 summarizes our results. Colored panels, which tag cases when the Anodal group outperformed the remaining
groups in some way, appear primarily on the left half of the figure where executive-control demands are high (i.e., “high conflict” cases). This pattern generally holds, with the exception of four instances on the right half of the figure; these represent cases when heightened task difficulty improved as a function of Anodal stimulation. Taken together, these results suggest that Anodal stimulation of left LPFC is associated with consistent benefits for cases tapping executive-control. We also note a similar pattern for difficult task conditions that do not involve resolving interference.

To recap, on the $n$-back task, we observed an effect of tDCS for target/non-target discrimi

Table 6. Estimate coefficients from linear mixed-effects models for $n$-back response criterion (Grier’s B’).

| Predictor                              | Coefficient | SE   | t-value |
|----------------------------------------|-------------|------|---------|
| Fixed Effects                          |             |      |         |
| Intercept                              | 0.138       | 0.035| 3.977*  |
| Conflict Level                         | 0.119       | 0.019| 6.095*  |
| Difficulty Level                       | -0.147      | 0.050| -2.949* |
| Conflict Level x Difficulty Level      | 0.085       | 0.039| 2.189*  |
| Anodal vs. Cathodal                    | 0.118       | 0.050| 2.377*  |
| Anodal vs. Sham                        | 0.009       | 0.050| 0.177   |
| Sham vs. Cathodal                      | 0.107       | 0.051| 2.101*  |
| Conflict Level x Anodal/Cathodal       | 0.023       | 0.028| 0.839   |
| Conflict Level x Anodal/Sham           | -0.010      | 0.028| -0.355  |
| Conflict Level x Sham/Cathodal         | 0.014       | 0.029| 0.479   |
| Difficulty Level x Anodal/Cathodal     | 0.015       | 0.071| 0.208   |
| Difficulty Level x Anodal/Sham         | 0.034       | 0.072| 0.477   |
| Difficulty Level x Sham/Cathodal       | -0.022      | 0.077| -0.291  |
| Conflict Level x Difficulty Level x Anodal/Cathodal | 0.122 | 0.055 | 2.200* |
| Conflict Level x Difficulty Level x Anodal/Sham | -0.041 | 0.056 | -0.729 |
| Conflict Level x Difficulty Level x Sham/Cathodal | 0.124 | 0.058 | 2.140* |
| Random Effects                         |             |      |         |
| Subjects (Intercept)                   | 0.0301      |      |         |
| Subjects (Difficulty Level)            | 0.0573      |      |         |
| Residuals                              | 0.0241      |      |         |

Difficulty Level refers to the $n$-level contrast of 2-back and 4-back, and Conflict Level refers to the lure presence contrast of blocks with versus without lures. Bold indicates coefficients that are significant. SE = standard error

*significant at the p<0.05 level

doi:10.1371/journal.pone.0141417.t006
Second, the Cathodal group was more conservative than the remaining groups, indicating that cathodal stimulation prompted more conservative responding compared to anodal and sham stimulation; this pattern is consistent with at least one other report demonstrating that anodal stimulation gives rise to less conservative n-back response thresholds [113]. Another plausible explanation for these data is that participants receiving cathodal stimulation may have engaged in a compensatory task-specific strategy to avoid false alarming to non-targets. Additional work should systematically explore the replicability of this cathode-based impairment on the n-back task. Finally, because n-back was always performed after the reading task, it is possible that the effects we observed were due, in part, to the limited amount of simultaneous (“online”) stimulation. That is, much of the n-back task was performed after the 30-minute stimulation period concluded. Even so, prior work indicates that anodal stimulation of left LPFC improves n-back accuracy for up to 30 minutes following stimulation [57]. Although much work demonstrates convincing online and offline effects [114–115], only some attempts have been made to understand the temporal properties of stimulation [32], which may be an important source of variability that contributed to our findings and that future studies should explore.

Fig 7. N-back response thresholds. Average n-back response criterion (Grier’s B’) for each stimulation group and task condition. Grier’s B’ is a non-parametric signal detection index of participants’ bias to respond ‘target’ or ‘non-target.’ A higher Grier’s B’ value corresponds to a conservative bias to say ‘non-target,’ while a lower Grier’s B’ indexes a higher likelihood of judging an item to be a ‘target.’ Error bars = ±1 standard error of the mean.

doi:10.1371/journal.pone.0141417.g007
On the sentence reading task, we observed several novel results favoring the Anodal group. First, compared to cathodal and sham, anodal stimulation resulted in higher accuracy on comprehension questions following ambiguous garden-path sentences, but not unambiguous control sentences. Although this result corroborates the discriminatory role of left LPFC for sentence processing scenarios with heightened executive-control demands [8], the reading time data paint a slightly different picture. We observed a positive effect of anodal stimulation for difficult ambiguous and unambiguous sentences (i.e., those with an additional modifier phrase). That is, the benefits of left LPFC stimulation were not limited exclusively to real-time processing decisions involving executive-control. Interestingly, further assessment of this analogous factor in relative clause constructions did not reveal any effects of stimulation. The difficult sentence type (object-extracted clause) and all long sentences were read equally quickly regardless of stimulation group assignment, suggesting that left LPFC may not service all linguistically complex input, but rather supports certain cases of real-time sentence processing [20]. Interestingly, cathodal and sham stimulation did not differ in their performance profiles for garden-path recovery or relative clause parsing, providing some evidence that cathodal stimulation does not result in behavioral changes as strong as those routinely observed with anodal stimulation [116–117].

**Difficulty versus Executive-Control Demands**

The distinction that we make between conditions with heightened executive-control demands versus those with elevated difficulty due to factors other than information-conflict is one that has been fleshed out elsewhere. This distinction has been articulated in terms of interference-resolution versus working memory maintenance [118–119], non-mnemonic versus mnemonic processing [27,120–121], and functional versus architectural abilities [122]. Thus, there is some impetus to disentangle these processing demands when considering the unique role of left LPFC for executive-control. We argue that our findings offer one such attempt to assess the
unique role of executive-control (separate from task-difficulty) in higher-level cognitive domains like language.

Related work suggests that general-purpose executive-control and processing associated with domain-specific difficulty are supported by neighboring neural areas within left LPFC [22,123]. This opens up another potential explanation for our mixed results. Namely, we observed that some Stimulation effects interacted with Conflict-Level only while others hinged on Difficulty-Level. Perhaps the adjacent anatomical nature of regions reputed to support executive-control and task-specific difficulty means that tDCS led to changes in conditions with both processing demands. Although we used “high definition” electrodes to administer the current, the technique is still lacking the necessary focal imprecision to discriminate among nearby regions. Ideally, in future work, anatomical variability across participants should be accounted for by identifying anode and cathode locations on the basis of individualized structural and functional information [52,124–125]. Moreover, high-definition montages arranged in a 4x1 ring can be combined with subject-by-subject anatomical information to provide the cleanest avenue to target neural tissue functionally responsive to conditions tapping executive-control versus task-specific difficulty [126–127].

Our current design relies on proper comparisons of minimally different conditions to parametrically introduce executive-control demands and task difficulty; however, it is possible that our results are still driven by an amalgam of cognitive mechanisms that we have not considered or accounted for here. For instance, the electrode sites used in the present study tap executive control (F3) and visual processing (O1), bringing to the forefront the possibility that impairing one ability while boosting the other might offset the intended effects of stimulation in important ways [128]. Given that the current reading and n-back tasks rely on visual processing, the lack of cathodal findings here could be, in part, due to the dynamic interplay of these two cognitive systems. It is possible that the positive effects of anodal stimulation over one region could overwhelm any simultaneous cathodal effects over another region. Future work might probe this possibility by testing the effects of electrode placement within the context of a multifocal stimulation approach [36].

It is also possible that the present design could benefit from fine-grained outcome measures, including functional imaging, connectivity indices, or eye movements. The lattermost option would remove some demands associated with our current reading task; it involved a self-paced moving-window design, which prevents naturalistic text processing and places a premium on working memory resources such that later arriving words obliterate prior ones [95,129]. Finally, the strongest tDCS reports incorporate some level of computational modeling to identify unique mechanistic underpinnings [130]. Some combination of the abovementioned improvements is liable to create the best scenario for interpreting stimulation-mediated changes in behavior.

**Brain Stimulation Considerations**

To evaluate the effects of Anodal stimulation, our design included two comparison groups (Cathodal and Sham). Fig 8 depicts conditions when Anodal stimulation leads to better performance relative to Sham stimulation (denoted in red), Cathodal stimulation (denoted in green), or both control conditions (denoted in blue). Although Anodal stimulation typically improves performance, it does so with respect to different comparison groups. Generally, the Anodal group outperforms the Cathodal group on all measures except for reading time on long garden-path sentences. The Sham group, on the other hand, only underperforms relative to the Anodal group on high-difficulty cases as measured by 4-back discriminability and reading time on long garden-path sentences. The lack of a difference between the Anodal and Sham groups
for comprehension accuracy is trending in the anticipated direction, such that the Anodal group is numerically more accurate than the Sham group on questions following ambiguous sentences (see right panels of Fig 3). Interestingly, when we compare performance between the Cathodal and Sham groups, we only find effects for \( n \)-back response criterion, such that the Cathodal group is more conservative than the remaining stimulation groups. No other measures revealed a distinction between the Cathodal and Sham groups. This pattern is contrary to some researchers’ findings [34,114,131], though consistent with others’ [116–117]. Take together, the current study provides some evidence for the efficacy of cathodal stimulation as an active control for anodal stimulation under some situations.

Brain stimulation offers an acute approach to evaluate brain-behavior relationships, as well as the linking hypotheses governing these relationships; however, there are several methodological limitations of tDCS worth considering. As touched on in the previous section, more precise electrode placement is a prerequisite to ensure that the same brain region is targeted across individuals. Our approach used canonical neuroanatomical markers (i.e., prescribed distances from the inion and nasion) to place the electrodes, but MRI-supported electrode arrangements offer an alternative to mitigate some uncertainty about which regions are receiving current ([132], but see [133] for arguments on the consistency across brains). Nevertheless, stimulation is still not necessarily focalized to the brain regions directly under the anode [115,134–135]. This may be due to reversals in polarity that occur across cerebral folds near the electrode site, such that the electrode montage does not always dictate consistent current flow [130]. Modeling the current on an individual subject basis by relying on structural and functional scans may help to understand and minimize this issue. A second limitation of tDCS is that almost all higher-level cognitive tasks, including executive-control, are supported by large-scale functional networks that include areas other than those routinely targeted by stimulation techniques [136–138]. Fortunately, initial evidence indicates that tDCS leads to changes on a network-wide level [139], yet the question of focality and precision of stimulation remains [39]. Exciting new research suggests that we may be able to rely on graph theory to target “network hubs” to elicit the largest network-level effects [140]. A final concern stems from a recent observation that not every person responds to tDCS stimulation. This may be due to variability in neuronal orientation or to other factors described above [141]. One way to combat this is to collect data from a sufficiently large sample, as we have done here.

Implications

We sidestep some of the methodological limitations common to tDCS by leveraging our interpretations on 1) our design with minimal within-task control conditions and 2) converging evidence from other methods and populations that hypothesize a clear role of executive-control in certain memory and language task conditions. The current findings provide additional evidence for left LPFC as the mediating force behind the linking hypothesis involving executive-control for garden-path recovery. In addition to these theoretical implications, the current results may be harnessed into applications for special populations. Specifically, we believe that these findings may be used to guide the development of interventions for patients with focal insult to left LPFC. Indeed, the number of successful attempts to use tDCS to improve abilities in individuals with aphasia and stroke patients with language-specific impairments is growing [65,67,142–146].

The present results may also have implications for healthy individuals. In particular, intervention-based training is a complementary tool that may also temporarily enhance higher-level cognitive abilities, like language and memory performance. Some groups have begun combining both methods and have found mixed results [115,147–151]. It is possible that with
appropriate linking hypotheses between training and transfer measures, joint tDCS/cognitive training interventions may give rise to improvements in sentence processing under difficult conditions, replicating prior cognitive training findings in this area [28]. Regardless, our results offer some promise of using tDCS in a single-session to determine appropriate training/transfer task combinations [27], and importantly, they add to the mounting evidence for the selective role of left LPFC-mediated executive-control for tasks in the language domain.

**Supporting Information**

**S1 Table. Sentence stimuli used in the reading task.** All critical sentence versions used in the experiment for the garden-path and relative clause constructions.

(PDF)

**S1 File. Participant data.** Compressed file containing data files from the N-Back Task (response times and accuracy for each trial) and Reading Task (word-by-word button press times and comprehension accuracy for each trial), as well as a separate file with participant information including group assignment and demographic information.

(ZIP)

**Acknowledgments**

The authors thank members of the Educational Psychology Psycholinguistics and Lifelong Brain and Cognition Labs for their assistance with collecting and scoring data, especially Kristen Michon, Michael Nosek, John Capozzo, and Kathryn Johnson. Finally, a portion of this work was presented at the 28th Annual CUNY Conference on Human Sentence Processing (Los Angeles, California) and the 21st Annual Conference on Architectures and Mechanisms for Language Processing (Valletta, Malta). We thank the attendees for their helpful comments and suggestions.

**Author Contributions**

Conceived and designed the experiments: EH KC AK NW. Performed the experiments: EH NW. Analyzed the data: EH. Contributed reagents/materials/analysis tools: EH AK. Wrote the paper: EH NW.

**References**

1. Botvinick MM, Braver TS, Barch DM, Carter CS, Cohen JD. Conflict monitoring and cognitive control. Psychol Rev. 2001; 108(3):624–652. PMID: 11488380
2. Miller EK, Cohen JD. An integrative theory of prefrontal cortex function. Annu Rev Neurosci. 2001; 24:167–202. PMID: 11283309
3. Norman W, Shallice T. Attention to action. In: Davidson RJ, Schwartz GE, Shapiro D, editors. Consciousness and self regulation: advances in research and theory. New York: Plenum; 1986. p. 1–18.
4. Altmann GT, Kamide Y. Incremental interpretation at verbs: restricting the domain of subsequent reference. Cognition. 1999; 73:247–264. PMID: 10585518
5. Badre D, Poldrack RA, Paré-Blagoev EJ, Insler R, Wagner AD. Dissociable controlled retrieval and generalized selection mechanisms in ventrolateral prefrontal cortex. Neuron. 2005; 47:907–918. PMID: 16157284
6. Bialystok E. Bilingualism in development: language, literacy, and cognition. New York: Cambridge University Press; 2001.
7. Kuperberg GR. Neural mechanisms of language comprehension: challenges to syntax. Brain Res. 2007; 1146:23–49. PMID: 17400197
8. Novick JM, Trueswell JC, Thompson-Schill SL. Cognitive control and parsing: reexamining the role of Broca’s area in sentence comprehension. Cogn Affect Behav Neurosci. 2005; 5:263–281. PMID: 16396089
9. Novick JM, Trueswell JC, Thompson-Schill SL. Broca’s area and language processing: evidence for the cognitive control connection. Lang Linguist Compass. 2010; 4:906–924.
10. Thompson-Schill SL, D’Esposito M, Aguirre GK, Farah MJ. Role of left prefrontal cortex in retrieval of semantic knowledge: a re-evaluation. Proc Natl Acad Sci USA. 1997; 94:14792–14797. PMID: 9405692
11. Vuong LC, Martin RC. The role of LIFG-based executive control in recovery from garden-paths during sentence comprehension. Front Psychol. 2014; doi: 10.3389/conf.fpsyg.2014.6.00044
12. Badre D, Wagner AD. Left ventrolateral prefrontal cortex and the cognitive control connection. Lang Linguist Compass. 2010; 4:906–924.
13. Kan IP, Thompson-Schill SL. Effect of name agreement on prefrontal activity during overt and covert picture naming. Cogn Affect Behav Neurosci. 2004; 4:33–57. PMID: 15259888
14. Mason RA, Just MA, Keller TA, Carpenter PA. Ambiguity in the brain: what brain imaging reveals about the processing of syntactically ambiguous sentences. J Exp Psychol Learn Mem Cogn. 2003; 29:1319–1338. PMID: 14622064
15. Thompson-Schill SL, D’Esposito M, Kan IP. Effects of repetition and competition on prefrontal activity during word generation. Neuron. 1999; 23:513–522. PMID: 10433263
16. Ye Z, Zhou X. Involvement of cognitive control in sentence comprehension: evidence from ERPs. Brain Res. 2008; 1203:103–115. doi: 10.1016/j.brainres.2008.01.095 PMID: 18313650
17. Robinson G, Blair J, Cipolotti L. Dynamic aphasia: an inability to select between competing verbal responses? Brain; 121:77–89. PMID: 9549489
18. Hamilton AC, Martin RC. Dissociations among tasks involving inhibition: A single-case study. Cogn Affect Behav Neurosci. 2005; 5:1–13. PMID: 15913003
19. Vuong LC, Martin RC. LIFG-based attentional control and the resolution of lexical ambiguities in sentence context. Brain Lang. 2011; 116:22–32. doi: 10.1016/j.bandl.2010.09.012 PMID: 20971900
20. Thothathiri M, Trueswell JC, Thompson-Schill SL. (2012). Parametric effects of syntactic-semantic conflict in Broca’s area during sentence processing. Brain and Language, 120(3), 259–264. doi:10.1016/j.bandl.2011.12.004 PMID: 22225974
21. Fedorenko E. The role of domain-general cognitive control in language comprehension. Front Psychol. 2014; 5:335. doi: 10.3389/fpsyg.2014.00335 PMID: 24803909
22. Fedorenko E, Duncan J, Kanwisher N. Language-selective and domain-general regions lie side by side within Broca’s area. Curr Biol. 2012; 22:2059–2062. doi: 10.1016/j.cub.2012.09.011 PMID: 23063434
23. Jonides J, Nee DE. Brain mechanisms of proactive interference in working memory. Neuroscience. 2006; 139:181–193. PMID: 16337090
24. Nelson JK, Reuter-Lorenz PA, Sylvester CC, Jonides J, Smith EE. Dissociable neural mechanisms underlying response-based and familiarity-based conflict in working memory. Proc Natl Acad Sci USA. 2003; 100:11171–11175. PMID: 12958206
25. January D, Trueswell JC, Thompson-Schill SL. Co-localization of Stroop and syntactic ambiguity resolution in Broca’s Area: implications for the neural basis of sentence processing. J Cogn Neurosci. 2009; 21(12):2343–2344. doi: 10.1162/jocn.2008.21179 PMID: 19199402
26. Ye Z, Zhou X. Executive control in language processing. Neurosci Biobehav Rev. 2009; 33:1168–1177. doi: 10.1016/j.neubiorev.2009.03.003 PMID: 19747595
27. Hussey EK, Novick JM. The benefits of executive control training and the implications for language processing. Front Psychol. 2012; 3:158. doi: 10.3389/fpsyg.2012.00158 PMID: 22661962
28. Novick JM, Hussey EK, Teubner-Rhodes SE, Harbison JI, Bunting MR. Clearing the garden-path: improving sentence processing through cognitive control training. Lang Cogn Process. 2014; 29 (2):186–217.
29. Dahlin E, Neely AS, Larsson A, Bäckman L, Nyberg L. Transfer of learning after updating training mediated by the striatum. Science. 2008; 320:1510–1512. doi: 10.1126/science.1155466 PMID: 18556560
30. Oelhafen S, Nikolaidis A, Padovani T, Blaser D, Koening T, Perrig WJ. Increased parietal activity after training of interference control. Neuropsychologia. 2013; 51(13):2781–2790. doi: 10.1016/j. neuropsychologia.2013.08.012 PMID: 23982078
31. Persson J, Larsson A, Reuter-Lorenz PA. Imaging fatigue of interference control reveals the neural basis of executive resource depletion. J Cogn Neurosci. 2013; 25(3):338–351. doi: 10.1162/jocn_a_00321 PMID: 23163416
32. Nitsche MA, Paulus W. Sustained excitability elevations induced by transcranial DC motor cortex stimulation in humans. Neurology. 2001; 57:1899–1901. PMID: 11723286
33. Purpura DP, McMurtry JG. Intracellular activities and evoked potential changes during polarization of motor cortex. J Neurophysiol. 1965; 28:166–185. PMID: 14244793
34. Utz KS, Dimova V, Oppenländer K, Kerkhoff G. Electrified minds: transcranial direct current stimulation (tDCS) and galvanic vestibular stimulation (GVS) as methods of non-invasive brain stimulation in neuropsychology—a review of current data and future implications. Neuropsychologia. 2010; 48 (10):2789–2810. doi: 10.1016/j.neuropsychologia.2010.06.002 PMID: 20542047
35. Nitsche MA, Doehmes S, Karakose T, Antal A, Liebetanz D, Lang N, et al. Shaping the effects of transcranial direct current stimulation of the human motor cortex. J Neurophysiol. 2007; 97(4):3109–3117. PMID: 17251360
36. Ruffini G, Fox MD, Ripolles O, Miranda PC, Pascual-Leone A. Optimization of multifocal transcranial current stimulation for weighted cortical pattern targeting from realistic modeling of electric fields. Neuroimage. 2014; 89:216–225. doi: 10.1016/j.neuroimage.2013.12.002 PMID: 24345389
37. Berryhill ME, Peterson DJ, Jones KT, Stephens JA. Hits and misses: leveraging tDCS to advance cognitive research. Front Psychol. 2014; 5:800. doi: 10.3389/fpsyg.2014.00800 PMID: 25120513
38. Horvath JC, Forte JD, Carter O. Evidence that transcranial direct current stimulation (tDCS) generates little-to-no reliable neurophysiologic effect beyond MEP amplitude modulation in healthy human subjects: A systematic review. Neuropsychologia. 2015; 66:213–236. doi: 10.1016/j.neuropsychologia.2014.11.002 PMID: 25456566
39. Coffman BC, Clark VP, Parasuraman R. Battery powered thought: enhancement of attention, learning, and memory in healthy adults using transcranial Direct Current Stimulation. Neuroimage. 2014; 85:897–910.
40. Antal A, Paulus W. Transcranial direct current stimulation and visual perception. Perception. 2008; 37 (3):367–374. PMID: 18491714
41. Sparing R, Dafotakis M, Meister IG, Thirugnanasambandam N, Fink GR. Enhancing language performance with non-invasive brain stimulation-a transcranial direct current stimulation study in healthy humans. Neuropsychologia. 2008; 46:261–268. PMID: 17804023
42. Capone F, Capone G, Ranieri F, Di Pino G, Orichio G, Di Lazzaro V. The effect of practice on random number generation task: a transcranial direct current stimulation study, Neurobiol Learn Mem. 2014; 114:51–57. doi: 10.1016/j.nlm.2014.04.013 PMID: 24811195
43. Fregni F, Boggio P, Nitsche M, Bermpohl F, Antal A, Feredoes E, et al. Anodal transcranial direct current stimulation of prefrontal cortex enhances working memory. Exp Brain Res. 2005; 166(1):23–30. PMID: 15999258
44. Jacobson L, Javitt DC, Lavidor M. Activation of inhibition: diminishing impulsive behavior by direct current stimulation over the inferior frontal gyrus. J Cogn Neurosci. 2011; 23(11):3380–3387. doi: 10.1162/jocn_a_00020 PMID: 21452949
45. Janacsek K, Ambrus GG, Paulus W, Antal A, Nemeth D. Right hemisphere advantage in statistical learning: evidence from a probabilistic sequence learning task. Brain Stimul. 2015; 7(6):773–783. doi: 10.1016/j.brs.2014.10.003 PMID: 25456566
46. Kincses T, Antal A, Nitsche M, Bartfai O, Paulus W. Facilitation of probabilistic classification learning by transcranial direct current stimulation of the prefrontal cortex. Neuropsychologia. 2004; 42(1):113–117. PMID: 14615081
47. Cerruti C, Schlaug G. Anodal transcranial direct current stimulation of the prefrontal cortex enhances complex verbal associative thought. J Cogn Neurosci. 2009; 21(10):1980–1987. doi: 10.1162/jocn.2008.21143 PMID: 18855556
48. Dockery CA, Hueckel-Weng R, Birbaumer N, Plewnia C. Enhancement of planning ability by transcranial direct current stimulation. J Neurosci. 2009; 29(22):7271–7277. doi: 10.1523/JNEUROSCI.0065-09.2009 PMID: 19494149
49. Javadi AH, Walsh V. Transcranial direct current stimulation (tDCS) of the left dorsolateral prefrontal cortex modulates declarative memory. Brain Stimul. 2012; 5(3):231–241. doi: 10.1016/j.brs.2011.06.007 PMID: 21840287
51. Javadi AH, Cheng P, Walsh V. Short duration transcranial direct current stimulation (tDCS) modulates verbal memory. Brain Stimul. 2012; 5(4):468–474. doi: 10.1016/j.brs.2011.08.003 PMID: 21962975

52. Meinzner M, Jähnigen S, Copland DA, Darkow R, Grittmann A, Avirame K, et al. Transcranial direct current stimulation over multiple days improves learning and maintenance of a novel vocabulary. Cortex. 2014; 50:137–147. doi: 10.1016/j.cortex.2013.07.013 PMID: 23988131

53. Zwissler B, Sperber C, Aigeldinger S, Schindler S, Kissler J, Plewnia C. Shaping memory accuracy by left prefrontal transcranial direct current stimulation. J Neurosci. 2014; 34(11):4022–4026. doi: 10.1523/JNEUROSCI.5407-13.2014 PMID: 24623779

54. Jeon SY, Han SJ. Improvement of the working memory and naming by transcranial direct current stimulation. Ann Rehabil Med. 2012; 36(5):585–595. doi: 10.5535/arm.2012.36.5.585 PMID: 23185722

55. Harty S, Robertson IH, Miniussi C, Sheehy OC, Devine CA, McCrerey S, et al. Transcranial direct current stimulation over right dorsolateral prefrontal cortex enhances error awareness in older age. J Neurosci. 2014; 34(10):3646–3652. doi: 10.1523/JNEUROSCI.5308-13.2014 PMID: 24599463

56. Gladwin TE, den Uyla TE, Fregni F. Enhancement of selective attention by tDCS: interaction of an old and a novel word. J Neurosci. 2014; 34:861–869. doi: 10.1523/JNEUROSCI.5115-13.2014 PMID: 24535600

57. Perrin L, Lupyan G. The role of language in multi-dimensional categorization: evidence from transcranial direct current stimulation and exposure to verbal labels. Brain Lang. 2014; 135:66–72. doi: 10.1016/j.bandl.2014.05.005 PMID: 24980415

58. Ohn SH, Park C-I, Yoo W-K, Ko M-H, Choi KP, Kim G-M, et al. Temporal breakdown of the plasticity enhancement effect of transcranial direct current stimulation on the enhancement of working memory. Neuroreport. 2008 Jan 8; 19(1):43–7. doi: 10.1097/WNR.0b013e32822adfd PMID: 18281890

59. Brunoni AR, Vanderhasselt MA. Working memory improvement with non-invasive brain stimulation of the dorsolateral prefrontal cortex: a systematic review and meta-analysis. Brain Cogn. 2014; 86:1–9. doi: 10.1016/j.bandc.2014.01.008 PMID: 24514153

60. Gray JR, Chabris CF, Braver TS. Neural mechanisms of general fluid intelligence. Nat Neurosci. 2003; 6:316–322. PMID: 12592404

61. Kane M, Conway A, Niwa T, Caffese G. Working memory, attention control, and n-back task: a question of construct validity. J Exp Psychol Learn Mem Cogn. 2007; 33(3):615–622. PMID: 17470009

62. deVries MH, Barth AC, Maiworm S, Knecht S, Zwitserlood P, Flöel A. Electrical stimulation of Broca’s region enhances implicit learning of an artificial grammar. J Cogn Neurosci. 2010; 22(11):2427–2436. doi: 10.1162/jocn.2009.21385 PMID: 19925194

63. Perry L, Lupyan G. The role of language in multi-dimensional categorization: evidence from transcranial direct current stimulation and exposure to verbal labels. Brain Lang. 2014; 135:66–72. doi: 10.1016/j.bandl.2014.05.005 PMID: 24980415

64. Monti BC, Ferrucci R, Fumagalli M, Mameli F, Cogiamanian F, Ardolino G, et al. Transcranial direct current stimulation (tDCS) and language. J Neurol Neurosurg Psychiatry. 2013; 84:832–837. doi: 10.1136/jnnp-2012-302825 PMID: 23138766

65. Baker JM, Rorden C, Fridriksson J. Using transcranial direct-current stimulation to treat stroke patients with aphasia. Stroke. 2010; 41:1229–1234. doi: 10.1162/jocn.2010.21579 PMID: 20946060

66. Fertonani A, Rosini S, Cotelli M, Rossini PM, Miniussi C. Naming facilitation induced by transcranial direct current stimulation. Behav Brain Res. 2010; 208:311–318. doi: 10.1016/j.bbr.2009.10.030 PMID: 19883697

67. Fiori V, Coccia M, Marinelli CV, Vecchi V, Bonifazi S, Ceravolo MG, et al. Transcranial direct current stimulation improves word retrieval in healthy and nonfluent aphasics. J Clin Neurosci. 2011 Sep; 23(9):2309–23. doi: 10.1111/j.1217-0096.2009.08634.x PMID: 21091293

68. Holland R, Leff AP, Josephs O, Galea JM, Desikan M, Price CJ, et al. Speech facilitation by left inferior frontal cortex stimulation. Curr Biol. 2011; 21:1403–1407. doi: 10.1016/j.cub.2011.07.021 PMID: 21820308

69. Cattaneo Z, Pisoni A, Papagno C. Transcranial direct current stimulation over Broca’s region improves phonemic and semantic fluency in healthy individuals. Neurosci. 2011; 183:64–70.

70. Iyer MB, Mattu U, Grafman J, Lomarev M, Sato S, Wassermann EM. Safety and cognitive effect of frontal DC brain polarization in healthy individuals. Neurology. 2005 Mar 8; 64(5):872–878. doi: 10.1212/01.wnl.0000147750.23188.89.

71. Pereira JB, Junqué C, Bartrés-Faz D, Martí MJ, Sala-Llonch R, Compta Y, et al. Modulation of verbal fluency networks by transcranial direct current stimulation (tDCS) in Parkinson’s disease. Brain Stimul. 2013 Jan; 6(1):16–24. doi: 10.1016/j.brs.2012.01.006 PMID: 22410476
72. Pisoni A, Vernice M, Iasevoli L, Cattaneo Z, Papagno C. Guess who? Investigating the proper name processing network by means of tDCS. Neuropsychologia. 2015; 66:267–78. doi:10.1016/j.neuropsychologia.2014.11.025 PMID: 25670534

73. Nozari N, Arnold JE, Thompson-Schill SL. The effects of anodal stimulation of the left prefrontal cortex on sentence production. Brain Stimul. 2014; 7(6):784–92. doi:10.1016/j.brs.2014.07.035 PMID: 25129401

74. Nozari N, Thompson-Schill SL. More attention when speaking: does it help or does it hurt? Neuropsychologia. 2013; 51:2770–2780. doi: 10.1016/j.neuropsychologia.2013.08.019 PMID: 24012690

75. Wirth M, Rahman RA, Kuencke J, Koenig T, Horn H, Sommer W, et al. Effects of transcranial direct current stimulation (tDCS) on behaviour and electrophysiology of language production. Neuropsychologia. 2011; 49(14):3989–3998. doi: 10.1016/j.neuropsychologia.2011.10.015 PMID: 22044650

76. Zaehle T, Sandmann P, Thorne JD, Jäncke L, Herrmann CS. Transcranial direct current stimulation of the prefrontal cortex modulates working memory performance: combined behavioural and electrophysiological evidence. BMC Neurosci. 2011; 12:2. doi: 10.1186/1471-2202-12-2 PMID: 21211016

77. Sela T, Ivry RB, Lavidor M. Prefrontal control during a semantic decision task that involves idiom comprehension: a transcranial direct current stimulation study. Neuropsychologia. 2012; 50(9):2271–2280. doi: 10.1016/j.neuropsychologia.2012.05.031 PMID: 22687558

78. McKinley RA, McIntire L, Bridges N, Goodyear C, Weisend MP. Acceleration of image analyst training with transcranial direct current stimulation. Behav Neurosci. 2013; 127:936–946. doi: 10.1037/a0034975 PMID: 23431718

79. Minhas P, Datta A, Bikson M. Cutaneous perception during tDCS: role of electrode shape and sponge salinity. Clin Neurophysiol. 2011; 122(4):637–638. doi: 10.1016/j.clinph.2010.09.023 PMID: 21075048

80. Klem GH, Lüders HO, Jasper HH, Elger C. The ten-twenty electrode system of the International Federation. Electroencephalogr Clin Neurophysiol. 1999; 52:3–6.

81. Jung Y-J, Kim J-H, Im C-H. COMETS: A MATLAB toolbox for simulating local electric fields generated by transcranial direct current stimulation (tDCS). Biomed Eng Lett. 2013 Apr 14; 3(1):39–46.

82. Fritsch B, Reis J, Martinowich K, Schambra HM, Ji Y, Cohen LG, et al. Direct current stimulation promotes BDNF-dependent synaptic plasticity: potential implications for motor learning. Neuron. 2010; 66(2):198–204. doi: 10.1016/j.neuron.2010.03.035 PMID: 20434997

83. Gandiga PC, Hummel FC, Cohen LG. Transcranial DC stimulation (tDCS): a tool for double-blind sham-controlled clinical studies in brain stimulation. Clin Neurophysiol. 2006; 117(4):845–850. PMID: 16427357

84. Christianson K, Hollingworth A, Halliwell J, Ferreira F. Thematic roles assigned along the garden path sentences arise from competing syntactic representations. J Mem Lang. 2013; 69(2):104–20.

85. Novick JM, Kan IP, Trueswell JC, Thompson-Schill SL. A case for conflict across multiple domains: memory and language impairments follow damage to ventrolateral prefrontal cortex. Cogn Neuropsychol. 2009; 26(6):527–567. doi: 10.1080/0264329090319367 PMID: 20183014

86. Ye Z, Zhou X. Conflict control during sentence comprehension: fMRI evidence. NeuroImage. 2009; 48:280–290. doi: 10.1016/j.neuroimage.2009.06.032 PMID: 19540923

87. Lewis RL, Vaisishth S. An activation-based model of sentence processing as skilled memory retrieval. Cogn Sci. 2005; 29:375–419. doi: 10.1207/s15516709cog0000_25 PMID: 21702779

88. Farmer TA, Misyak JB, Christiansen MH. Individual differences in sentence processing. In: Spivey M, Joannisse M, McRae K, editors. Cambridge Handbook of Psycholinguistics. Cambridge, UK: Cambridge University Press; 2012. p. 353–364.

89. Fedorenko E, Woodbury R, Gibson E. Direct evidence of memory retrieval as a source of difficulty in long-distance structural dependencies in language. Cogn Sci. 2013;(37: ) 2:378–394

90. Van Dyke JA, Lewis RL. Distinguishing effects of structure and decay on attachment and repair: a retrieval interference theory of recovery from misanalyzed ambiguities. J Mem Lang. 2003; 49(3):285–316.
94. Thothathiri M, Kimberg DY, Schwartz MF. The neural basis of reversible sentence comprehension: evidence from voxel-based lesion-symptom mapping in aphasia. J Cogn Neurosci. 2012; 24:212–222. doi: 10.1162/jocn_a_00118 PMID: 21861679
95. Just MA, Carpenter PA, Woolley JD. Paradigms and processes and in reading comprehension. J Exp Psychol Gen. 1982; 3:228–238.
96. Christianson K, Williams CC, Zacks RT, Ferreira F. Younger and older adults “Good-enough” interpretations of garden-path sentences. Discourse Process. 2006; 42(2):205–238. PMID: 17203135
97. Owen AM, McMillan KM, Laird AM, Bullmore E. N-back working memory paradigm: a meta-analysis of normative functional neuroimaging studies. Hum Brain Map, 2005; 25(1):46–59.
98. Obreauer K. Binding and inhibition in working memory: Individual and age differences in short-term recognition. J Exp Psychol Gen. 2005; 134(3):368–387. PMID: 1613265
99. Schmiedek F, Li S-C, Lindenberger U. Interference and facilitation in spatial working memory: age-associated differences in lure effects in the n-back paradigm. Psychol Aging. 2009; 24:203–210. doi: 10.1037/a0014685 PMID: 19290752
100. Szmalec A, Verbruggen F, Vandierendonck A, Kemps E. Control of interference during working memory updating. J Exp Psychol Hum Percept Perform. 2011; 37(1):137–151. doi: 10.1037/a0020365 PMID: 20731517
101. Jaeger FT. Categorical data analysis: Away from ANOVAs (transformation or not) and towards logit mixed models. J Mem Lan. 2008; 59(4):434–446.
102. Barr DJ, Levy R, Scheepers C, Tily HJ. Random effects structure for confirmatory hypothesis testing: keep it maximal. J Mem Lang. 2013; 68(3):255–278.
103. Mirman D. Minding the Brain [Internet]. Philadelphia: Dan Mirman. 2014 Feb—[cited 2015 May 10]. Available from: http://mindingthebrain.blogspot.com/2014/02/three-ways-to-get-parameter-specific-p.html
104. Enders CK, Tofighi D. Centering predictor variables in cross-sectional multilevel models: a new look at an old issue. Psychol Methods. 2007; 12(2):121–138. PMID: 17563168
105. Linck JA, Schwieter JW, Sunderman G. Inhibitory control predicts language switching performance in trilingual speech production. Biling. 2012; 15(3), 651–662.
106. Mirman D. Minding the Brain [Internet]. Philadelphia: Dan Mirman. 2013 April—[cited 2015 Aug 3]. Available from: http://mindingthebrain.blogspot.com/2013/04/multiple-pairwise-comparisons-for.html
107. Clifton C, Traxler MJ, Mohamed MT, Williams RS, Morris RK, Rayner K. The use of thematic role information in parsing: syntactic processing autonomy revisited. J Mem Lan. 2003; 49(3):317–334.
108. Sturt P. Semantic re-interpretation and garden path recovery. Cognition. 2007; 105:477–488. PMID: 17178115
109. Ferreira F, Clifton C. The independence of syntactic processing. J Mem Lan. 1986; 25(3):348–368.
110. Stanislaw H, Todorov N. Calculation of signal detection theory measures. Behav Res Methods Instrum Comput. 1999; (31:1):137–149.
111. Cole MW, Yarkoni T, Repov G, Anticevic A, Braver TS. Global connectivity of prefrontal cortex predicts cognitive control and intelligence. J Neurosci. 2012; 32(26):8988–8999. doi: 10.1523/JNEUROSCI.0536-12.2012 PMID: 22745498
112. Tschida A, Fellows LK. Lesion evidence that two distinct regions within prefrontal cortex are critical for n-back performance in humans. J Cogn Neurosci. 2009; 21(12):2263–2275. doi: 10.1162/jocn.2008.21172 PMID: 19199405
113. Oliveira JF, Zanlo TA, Valiengo L, Lotufo PA, Benseñor IM, Fregni F, et al. Acute working memory improvement after tDCS in antidepressant-free patients with major depressive disorder. Neurosci Lett. 2013; 537:60–64. doi: 10.1016/j.neulet.2013.01.023 PMID: 23370288
114. Nozari N, Woodard K, Thompson-Schill SL. Consequences of cathodal stimulation for behavior: When does it help and when does it hurt performance? PLoS One. 2014; 9(1):e84338. doi: 10.1371/journal.pone.0084338 PMID: 24409291
115. Martin D, Liu R, Alonzo A, Green M, Loo C. Use of transcranial direct current stimulation (tDCS) to enhance cognitive training: effect of timing of stimulation. Exp Brain Res. 2014; 232(10):3345–3351. doi: 10.1007/s00221-014-4022-x PMID: 24992897
116. Jacobson L, Koslowsky M, Lavidor M. tDCS polarity effects in motor and cognitive domains: a meta-analytical review. Exp Brain Res. 2011; 216(1):1–10. doi: 10.1007/s00221-011-2891-9 PMID: 21989847
117. Pirulli C, Fertonani A, Minussi C. Is neural hyperpolarization by cathodal stimulation always detrimental at the behavioral level? Front Behav Neurosci. 2014; 8:226. doi: 10.3389/fnbeh.2014.00226 PMID: 25018709
118. Friedman NP, Miyake A. The relations among inhibition and interference cognitive functions: a latent variable analysis. J Exp Psychol Gen. 2004; 133:101–135. PMID: 14979754

119. Miyake A, Friedman NP, Emerson MJ, Witzki AH, Howerton A, Wager TD. The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: a latent variable analysis. Cogn Psychol. 2000; 41:49–100. PMID: 10945922

120. D’Esposito M, Postle BR. The dependence of span and delayed-response performance on prefrontal cortex. Neuropsychologia. 1999; 37:1303–1315. PMID: 10530730

121. Kane MJ, Engle RW. Working memory capacity, proactive interference, and divided attention: limits on long-term memory retrieval. J Exp Psychol Learn Mem Cogn. 2000; 26:333–358.

122. Bartolotti J, Marian V. Language learning and control in monolinguals and bilinguals. Cogn Sci. 2012; 36:1129–1147. doi: 10.1111/j.1551-6709.2012.01243.x PMID: 22462514

123. Blank I, Kanwisher N, Fedorenko E. A functional dissociation between language and multiple-demand systems revealed in patterns of BOLD signal fluctuations. J Neurophysiol. 2014; 112(5):1105–1118. doi: 10.1152/jn.00884.2013 PMID: 24872535

124. Bikson M, Datta A. Guidelines for precise and accurate computational models of tDCS. Brain Stimul. 2012; 5:430–431. doi: 10.1016/j.brainstim.2011.06.001 PMID: 21782547

125. Datta A, Truong D, Minhas P, Parra LC, Bikson M. Inter-individual variation during transcranial direct current stimulation and normalization of dose using MRI-derived computational models. Front Psychiatry. 2012; 3:91. doi: 10.3389/fpsyg.2012.00091 PMID: 23097644

126. Edwards D, Cortes M, Datta A, Minhas P, Wassermann EM, Bikson M. Physiological and modeling evidence for focal transcranial electrical brain stimulation in humans: A basis for high-definition tDCS. NeuroImage. 2013; 74:266–275. doi: 10.1016/j.neuroimage.2013.01.042 PMID: 23370061

127. Kuo H-I, Bikson M, Datta A, Minhas P, Paulus W, Kuo M-F, et al. Comparing cortical plasticity induced by conventional and high-definition 4×1 ring tDCS: a neurophysiological study. Brain Stimul. 2013; 6(4):644–648. doi: 10.1016/j.brs.2012.09.010 PMID: 23149292

128. Bikson M, Datta A, Rahman A, Scaturro J. Electrode montages for tDCS and weak transcranial electrical stimulation: Role of “return” electrode’s position and size. Clin Neurophysiol. 2010; 121(12):1976–1978. doi: 10.1016/j.clinph.2010.05.020 PMID: 21035740

129. Witzel N, Witzel J, Forster K. Comparisons of online Reading paradigms: eye tracking, moving-window, and maze. J Psycholinguist Res. 2012; 41:105–129. doi: 10.1007/s10736-011-9179-x PMID: 22002037

130. Bestmann S, de Berker AO, Bonaiuto J. Understanding the behavioural consequences of noninvasive brain stimulation. Trends Cogn Sci. 2015; 19(1):13–20. doi: 10.1016/j.tics.2014.10.003 PMID: 25467129

131. Truong DQ, Magerowski G, Blackburn GL, Bikson M, Alonso-Alonso M. Computational modeling of transcranial direct current stimulation (tDCS) in obesity: Impact of head fat and dose guidelines. NeuroImage. 2013; 74:245–255. doi: 10.1016/j.neuroimage.2013.01.042 PMID: 23370061

132. Kim JH, Kim DW, Chang WH, Kim YH, Kim K, Im CH. Inconsistent outcomes of transcranial direct current stimulation changes connectivity of resting-state networks during fMRI. J Neurosci. 2011; 31(13):1129–1136. doi: 10.1523/JNEUROSCI.0542-11.2011 PMID: 22031874
140. Polanía R, Nitsche MA, Paulus W. Modulating functional connectivity patterns and topological functional organization of the human brain with transcranial direct current stimulation. Hum Brain Mapp. 2011; 32(8):1236–49. doi: 10.1002/hbm.21104 PMID: 20607750

141. López-Alonso V, Cheeran B, Río-Rodríguez D, Fernández-del-Olmo M. Inter-individual variability in response to non-invasive brain stimulation paradigms. Brain Stimul. 2014; 7:372e80.

142. Hamilton RH, Chrysikou EG, Coslett B. Mechanisms of aphasia recovery after stroke and the role of noninvasive brain stimulation. Brain Lang. 2011; 118(1–2):40–50. doi: 10.1016/j.bandl.2011.02.005 PMID: 21459427

143. Holland R, Crinion J. (2012). Can tDCS enhance treatment of aphasia after stroke? Aphasiology. 2012; 26:1169–1191. PMID: 23060684

144. Monti A, Cogiamanian F, Marceglia S, Ferrucci R, Mameli F, Mrakic-Sposta S, et al. Improved naming after transcranial direct current stimulation in aphasia. J Neurol Neurosurg Psychiatr. 2008; 79(4):451–453. PMID: 18096677

145. Schlaug G, Marchina S, Wan CY. The use of non-invasive brain stimulation techniques to facilitate recovery from post-stroke aphasia. Neuropsychol Rev. 2011; 21(3):288–301. doi: 10.1007/s11065-011-9181-y PMID: 21842404

146. Suzuki K, Fujiwara T, Tanaka N, Tsuiji T, Masakado Y, Hase K, et al. Comparison of the after-effects of transcranial direct current stimulation over the motor cortex in patients with stroke and healthy volunteers. Int J Neurosci. 2012; 122(11):675–681. doi: 10.3109/00207454.2012.707715 PMID: 22747238

147. Cappelletti M, Gessaroli E, Hithersay R, Mitolo M, Didino D, Kanai R, et al. Transfer of cognitive training across magnitude dimensions achieved with concurrent brain stimulation of the parietal lobe. J Neurosci. 2013; 33(37),14899–14907. doi: 10.1523/JNEUROSCI.1692-13.2013 PMID: 24027289

148. Ditye T, Jacobson L, Walsh V, Lavdor M. Modulating behavioral inhibition by tDCS combined with cognitive training. Exp Brain Res. 2012; 219(3),363–368. doi: 10.1007/s00221-012-3098-4 PMID: 22532165

149. Elmasry J, Loo C, Martin D. A systematic review of transcranial electrical stimulation combined with cognitive training. Restor Neurol Neurosci. 2015; Epub 2015 Jan 26. doi.org/10.3233/RNN-140473

150. Jones KT, Stephens JA, Alam M, Bikson M, Berryhill ME. Longitudinal neurostimulation in older adults improves working memory. PLoS One. 2015; 10(4):e0121904. doi: 10.1371/journal.pone.0121904 PMID: 25849358

151. Richmond LL, Wolk D, Chein J, Olson IR. Transcranial direct current stimulation enhances verbal working memory training performance over time and near transfer outcomes. J Cogn Neurosci. 2014; 26(11):2443–2454. doi: 10.1162/jocn_a_00657 PMID: 24742190