Brain and Language 188 (2019) 11–17

Contents lists available at ScienceDirect

Brain and Language

journal homepage: www.elsevier.com/locate/b&l

Transcranial direct current stimulation (tDCS) selectively modulates semantic information during reading

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ARTICLE INFO

Keywords:
tDCS
Semantics
Imageability
Reading
Stimulation
Angular gyrus

ABSTRACT

The left angular gyrus has long been implicated in semantic processing. Here we tested whether or not transcranial direct current stimulation (tDCS) over the left angular gyrus modulated reading performance. Adult readers (N = 77) (1) read aloud words that varied in degree of imageability, a semantic word property known to activate the angular gyrus, and (2) completed an N-back task (control task). Individuals were randomly assigned to either the anodal, cathodal or sham stimulation conditions. We found that anodal (p = 0.001) and cathodal (p < 0.001) stimulation impacted how imageability facilitates reading times such that readers who showed the largest imageability effects pre-stimulation showed the greatest reduction in these effects post-stimulation. No effects of stimulation were found in the sham group (p > 0.05) or for the control task (i.e., N-back; p > 0.05). These findings indicate that reading pathways can be modulated via brain stimulation (tDCS) to shift individuals' sensitivity to word-level characteristics, namely imageability.

1. Introduction

Visual word recognition engages a neural reading network that extends among brain regions involved in recognizing print (e.g., inferior temporal gyrus; Mechelli, et al., 2005; Mechelli, Josephs, Ralph, McClelland, & Price, 2006), extracting letter to sound representations (e.g., supramarginal gyrus; Sliwinska, Khadilkar, Campbell-Ratcliffe, Quevenco, & Devlin, 2012; posterior inferior frontal gyrus; Mechelli et al., 2006), and accessing/assessing meaning (e.g., angular gyrus; Binder, Desai, Graves, & Conant, 2009; anterior inferior frontal gyrus; Price, 2012). While this entire network becomes active during reading, the relative contribution of each region has been shown to be modulated through manipulations of stimulus properties (Mechelli et al., 2006) and task demands (Mechelli et al., 2005; Sliwinska et al., 2012; Sliwinska, James, & Devlin, 2015). More recently, researchers have been exploring the extent to which the relative contribution of regions in the reading network can be modulated by brain stimulation, including transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS). Here, we were interested in exploring the extent to which tDCS over one subcomponent of the reading network, the angular gyrus, impacted reading performance by modulating access to semantic word-level properties as indexed by word imageability effects.

1.1. Reading: Imageability

The angular gyrus is particularly sensitive to words/tasks that promote and/or require semantic access (Bedny & Thompson-Schill, 2006; Binder et al., 2009; Binder, Medler, Desai, Conant, & Liebenthal, 2005; Binder, et al., 2001), including tasks that are highly reliant on word meaning information (i.e., contexts including ambiguous words like 'bat') or items that have rich semantic representations (i.e., words that are highly imageable like 'rainbow'). Relevant to the present work, activity in the angular gyrus has been shown to be related to word imageability, defined as, 'the ease at which a word conjures a mental image' (p. 1800, Graves, Binder, Desai, Conant, & Seidenberg, 2010), whereby, increased activity was related to greater facilitation of imageability on response time (Strain, Patterson, & Seidenberg, 1995). Importantly, there is reported individual variability in the population's reliance on imageability, such that greater word imageability is associated with faster response times (i.e., a negative imageability slope value) for some individuals, and slower response times for others. Still others show relatively little impact of word imageability on response time. Beyond function, Graves et al., (2014) also showed that the volume of the white matter pathway connecting the angular gyrus and posterior superior temporal gyrus was related to the degree to which an individual's reading time was influenced by semantic imageability.

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https://doi.org/10.1016/j.bandl.2018.11.002
Received 25 April 2018; Received in revised form 15 October 2018; Accepted 10 November 2018
Available online 24 November 2018

More specifically, individuals with greater volume of this pathway showed greater facilitation effects for high versus low imageability words, suggesting individuals who are more susceptible to semantic effects during reading more actively engage connections within the semantic portion of the reading network.

1.2. Neuromodulation: Transcranial direct current stimulation

Beyond the measurement of functional (fMRI) and structural (DTI) properties associated with the angular gyrus, active brain stimulation also has provided evidence for the role of this region in semantic access. For example, TMS work has shown that disrupting activity in the angular gyrus actually impedes reading performance during tasks that require meaning-based information (Sliwinska et al., 2015). Notably, the effect was absent when stimulation was provided to the nearby supramarginal gyrus that is hypothesized to instead be involved in decoding the phonological properties of words (Démonet et al., 1992; Paulesu, Frith, & Frackowiak, 1993). Such work has been important for advancing our understanding of the role of the angular gyrus in the reading network; however, it remains to be seen whether the findings from brain stimulation techniques that alter neuronal functioning (i.e., TMS), generalize to brain stimulation techniques that potentially 'prime' or 'inhibit' the neuronal system (i.e., tDCS) (Stagg & Nitsche, 2011; Summers, Kang, & Cauraugh, 2015). In addition, there is evidence of individual variability in implicit reading strategies due to tradeoffs in the contribution of lexical and sub-lexical reading mechanisms during word recognition (Baron & Strawson, 1976). This variability in trading relations is apparent in the relative strength of imageability effects between readers. It thus seems reasonable that brain stimulation would have differential effects on performance depending on the degree to which an individual is sensitive to word imageability. Such questions have not yet been explored in the literature but are critical to providing a more comprehensive understanding of the role of the angular gyrus in modulating reading performance.

1.3. Summary

In summary, the present study sought to address the following research question: To what extent does tDCS over the angular gyrus impact individuals' susceptibility to word-level imageability? Given the previous literature on brain stimulation techniques and individual variability in reliance on word imageability, we hypothesized: (1) that active stimulation (i.e., anodal/facilitatory or cathodal/inhibitory) would impact individual sensitivity to imageability (i.e., slope values associated with imageability ratings/response time for each participant), although we make no hypotheses specific to a particular stimulation parameter as both anodal and cathodal stimulation would be a 'disruption' to an already efficient reading system; (2) that the non-active stimulation (i.e., sham) would not impact individual sensitivity to imageability.

2. Methods

2.1. Participants

A total of 77 healthy adults participated in this study (52 females; Mean age = 21.6; SD = 5.09), assigned randomly to each of the three stimulation conditions (N = 25 anodal; N = 26 cathodal; N = 26 sham). Participants were recruited from the University of Alberta (N = 30) and the University of Western Ontario (N = 47). All participants were tested in accordance with the institutional ethics requirements. All participants were right-handed, spoke English as their first language, and reported that they did not have a history of speech, language, or reading disorders, a history of migraines, seizures, or high blood pressure, or any hearing or vision problems that were not corrected.

2.2. Materials

All tasks were presented on a Windows-compatible computer using E-prime 2.0 presentation package (an LCD display was used at the University of Alberta and a CRT display was used at Western University). For the reading aloud task, we utilized the 465 monosyllabic English words outlined in Graves et al. (2010), as these words were carefully chosen so that word imageability[1] was not correlated with other critical word characteristics (i.e., written frequency, spelling-to-sound consistency, bigram frequency, letter length). The list was divided into two lists of 227 words that did not differ on the aforementioned characteristics, with each list randomly assigned to pre- or post-stimulation. The words appeared one at a time in the center of a computer screen in black, 40-point, bold, Courier New font, against a white background. The words were displayed for a maximum of 2500 ms. A standing microphone was placed in front of the individuals that (1) measured onset vocal response time and (2) signaled the experiment to advance upon receiving a voice onset trigger.

Participants also performed a second N-back control task before and after stimulation, which was used to assess the general effect of stimulation (real or sham) on general cognitive performance. Participants viewed a sequence of letters presented one at a time at 1500 ms interstimulus interval, and were required to press '1' if the current letter on the screen was identical to the letter from two instances prior, and otherwise to withhold a response if it was not presented two instances prior.

2.3. Stimulation protocol

A Chattanooga Iontophoresis Unit (DJO Devices LLC, Visa CA) was used to provide transcranial direct current stimulation. The unit can administer 0–160 mA of current per minute across one or two pairs of leads. In this study we administered current at one anode and one cathode site using 4.5 × 5 cm Pro Carbon C5015PR electrodes embedded within 5 × 7.5 cm sponges. The two electrodes were attached to a twin lead connector that was colour coordinated to indicate positive (anodal; red) and negative (cathodal; black) stimulation. Placement of the electrodes depended on the condition each participant received. For anodal stimulation, the positive electrode was placed over the left angular gyrus (location TP3 in accordance with the 10–20 stereotaxic coordinate system; Herwig, Satrapi, & Schonfeldt-Lecuona, 2003) and the negative electrode on the right upper arm. Participants received 13 min of tDCS. The anodal stimulation group received stimulation at 1 milliamp (mA) for the entire 13 min. For the cathode stimulation group, the positive electrode was placed on the arm and the negative electrode placed on the TP3 region of the head. Stimulation duration and procedure remained the same as anodal condition. For the sham stimulation group, the positive electrode was placed on the TP3 region of the head and the negative electrode was place on the upper right arm. A ramp up to 1 mA was given and then a ramp down to 0 mA over the first and last 30 s of the stimulation session, which provided the sensation of electrical stimulation but with only a brief cortical effect that was not likely to have a significant influence on neural processing. For all conditions, sponges were wet with a sodium chloride solution [0.9% (36 g/4 L) concentration] before stimulation and subsequently every five minutes until stimulation completion, to maintain a relatively stable current throughout the stimulation procedure as current will change with drying (Ambrus, Antal, & Paulus, 2011). Saline was added to the backs of sponges using a small syringe, without lifting the

[1] As outlined in Graves et al., (2010), imageability ratings were gathered from six different sources including: Bird et al. (2001), Clark and Paivio (2004), Cortese and Fugett (2004), Gilhooly and Logie (1980), Paivio et al. (1968), Toglia and Battig (1978). The imageability ratings (on a 1–7 point scale) of the 465 words used here ranged from 1.4 to 6.59 with a mean = 4.39.

sponges or electrodes from the scalp. Towels were used as a precaution to catch any “drips” to non-targeted areas of the scalp.

2.4. Procedure

This study was a single-blind experiment meaning that the individual subjects did not know which stimulation condition they were assigned to, but the experimenter was informed due to the need to set up and control the stimulation system. Each participant was randomly assigned to one of three stimulation conditions and the order of the word reading and control task (N-back) were counterbalanced within each group. Upon arrival, informed consent was obtained and the participant was seated.

Participants performed both behavioral tasks twice in a single session: immediately prior to stimulation, and again immediately after stimulation. Depending on the order determined prior, participants either completed the N-back task or the reading task first. The computer was moved in front of the participant and placed at arm’s length. A SHURE MX-185 microphone was secured on the forehead 10 cm from the mouth amplified and digitally recorded and an additional microphone (Audio-Technica), attached to the E-prime computer, was placed on a stand in front of the participant (microphone 2 in. from the mouth). Researchers first explained the task and the participant was then required to complete a practice set to ensure understanding of the tasks. For the N-back task, participants were required to press 1 if the current letter on the screen was identical to the letter from two instances prior. For the reading aloud task, participants were required to say the word on the screen. The E-prime microphone was used to advance the experiment once the word was read aloud.

Upon completion of both pre-tasks, the participants were prepared for stimulation. An EEG cap was used to identify the TP3 site according to the international 10–20 system. Cap placement was further standardized across participants by measuring the halfway point from nasion to inion and from left tragus to right tragus as the Cz (true centre) site, and 10% superior to the nasion as the FpZ site. Once the TP3 was marked, the cap was removed and the marked point served as the centre of the scalp electrode. The right upper arm was used as the second eletrode site. Both areas receiving the stimulation were scrubbed with Nuprep and rinsed with saline to assure sites were free contamination that could impede stimulation. The electrode was placed in a sponge that had been soaked in saline, placed on site and held in place using elasticized fabric bands. During the 13-minute stimulation period, participants completed a simple number identification task as a distraction task to control for the cognitive processes that were occurring at that time. This task was also controlled with E-Prime and required the participant to press the number on a keyboard corresponding to the number appearing on the screen.

Current density (Nitsche, et al., 2008) was calculated as 0.04 mA/cm^2. Current flow based on electrode plus sponge dimensions, is modeled using principles presented by Opitz, Paulus, Antunes, and Theilscher, (2015) and models presented in SimNIBS (http://simnibs.de/) (Thielscher, Antunes, & Saturnino, 2015), and spatially visualized on a canonical brain in Fig. 1.

2.5. Analysis

The effect of imageability was calculated as a slope value computed for each participant by regressing their response time onto the imageability of each item (ms change in RT per unit of change in imageability). Slopes were calculated separately pre- and post-stimulation allowing us to assess whether tDCS stimulation influenced the degree to which imageability affected an individual’s reading times. The independent variables in the current study were time (pre vs. post-stimulation), and stimulation condition (anodal, cathodal, sham). The dependent variables were response time, imageability slope value, and accuracy. An ANOVA was used to test for differences across the groups on the pre-stimulation dependent variables (i.e., to ensure the groups were comparable prior to stimulation).

To test our hypotheses, we compared mean imageability slopes pre- vs. post-stimulation within each stimulation group; a Bonferroni-corrected *p*-value of 0.017 was used, reflecting an alpha = 0.05 over three *t*-tests. To further test the impact of active stimulation on imageability slope values, we also assessed the relationship between pre-stimulation imageability slope values (predictor) and the post-pre stimulation imageability scores (criterion; i.e., difference score) for each stimulation condition, using simple linear regression. We assessed the subsequent results at a corrected *p*-value ($<$ 0.017, alpha = 0.05 divided by 3 for each stimulation condition).

3. Results

Participant-wise imageability slopes are depicted in Fig. 2A & B. We observed no significant difference between the groups on their pre-response times, $F(2, 74) = 1.347$, $p = 0.266$, pre-imageability slope values, $F(2, 74) = 0.315$, $p = 0.731$ or pre-accuracy, $F(2, 74) = 0.214$, $p = 0.808$, indicating that all groups were comparable prior to stimulation. Differences in pre vs. post response times, imageability slope values and accuracy were next tested for each stimulation group (see Table 1 and Fig. 3). One difference was found, whereby individuals in the cathodal stimulation group were significantly faster in responding post- (491.59 ms) vs. pre- (510.00 ms) stimulation, $t(25) = 2.848$, $p < 0.009$ (all other comparisons were not significant ($p > 0.05$)).

We then tested whether stimulation type had a significant effect on the imageability slope value. Analyses revealed significant relationships between pre-imageability slope and the change in imageability slope for both active stimulation conditions (anodal and cathodal; $F(1,23) = 15.32$, $p < 0.001$, $\beta = -0.632$ and $F(1,24) = 32.55$, $p < 0.001$, $\beta = -0.759$, respectively; see Fig. 4A and B). In both anodal and cathodal groups, as the pre-imageability slope went down, so too did the change in imageability slope. The sham condition did not reveal a similar effect, $F(1,24) = 3.09$, $p > 0.05$ (see Fig. 4C). While a one-way ANOVA indicates that the difference in imageability change scores (i.e., pre- post) did not differ among the groups, likely given the small range of imageability values and the sample sizes, $F(2, 74) = 0.667$, $p = 0.516$, the stimulation condition impacted the relationship between pre and post imageability slopes. Another way to conceptualize this is, if the effect of stimulation were nil, then pre- and post-imageability slope scores should be comparable as evidenced by a significant relationship. We tested this for each stimulation group using a Pearson correlation coefficient. The sham condition had a significant relationship between pre and post slope scores ($r = 0.469$, $p < 0.05$), whereas this correlation was not significant for either the anodal ($p = 0.465$) or the cathodal conditions ($p = 0.810$).

Using a series of paired samples *t*-tests, we found no differences between pre- and post-stimulation accuracy for the control N-back task in anodal ($p = 0.166$), cathodal ($p = 0.225$) or sham conditions ($p = 0.304$). Due to a coding error, response times for the N-back were only obtained for 45 participants. There was no significant difference between the groups on their pre-response times, $F(2, 40) = .680$, $p = 0.513$, indicating that all groups were comparable prior to stimulation. Differences in pre vs. post response times were tested for each stimulation group and all comparisons were not significant ($p > 0.12$).

4. Discussion

We examined the extent to which tDCS over the angular gyrus modulated reading out loud, and the extent to which any observed effect would be specific to reading sub-processes related to whole-word access. Also of interest, was the extent to which these effects would vary based on individual differences in reading style, as defined by the extent to which semantic factors influence the speed with which a reader can name a word aloud. We found that active stimulation served to

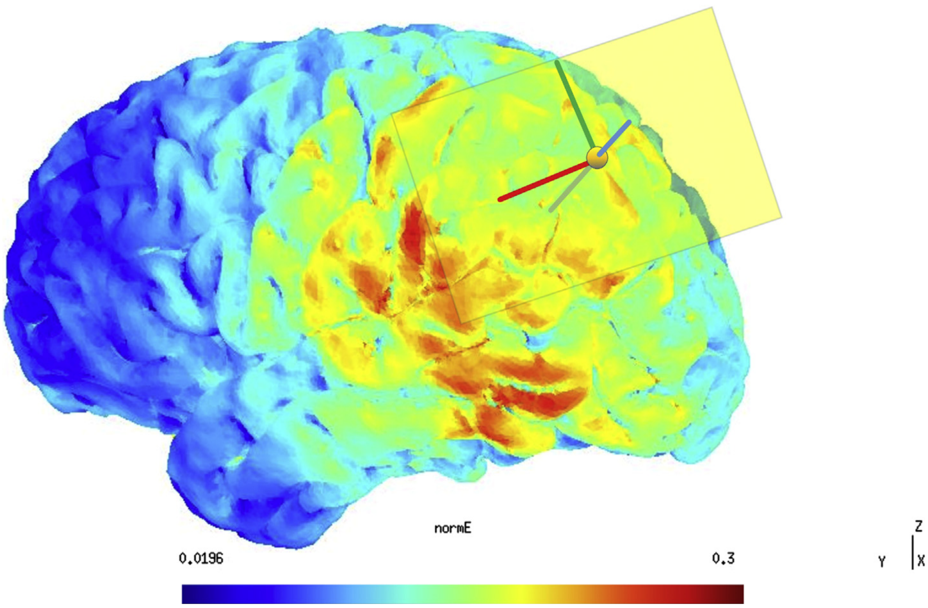

Fig. 1. Spatial estimates of the electrical current flow based on electrode placement over TP3 (Opitz et al., 2015; Thielscher et al., 2015. Electrode placement is depicted by the transparent rectangle on the cortex not accounting for scull curvature, direction of electrode current output is depicted in x, y & z axes. Electrical current flow is depicted using a colour scheme of red = higher current to blue = little to no current.

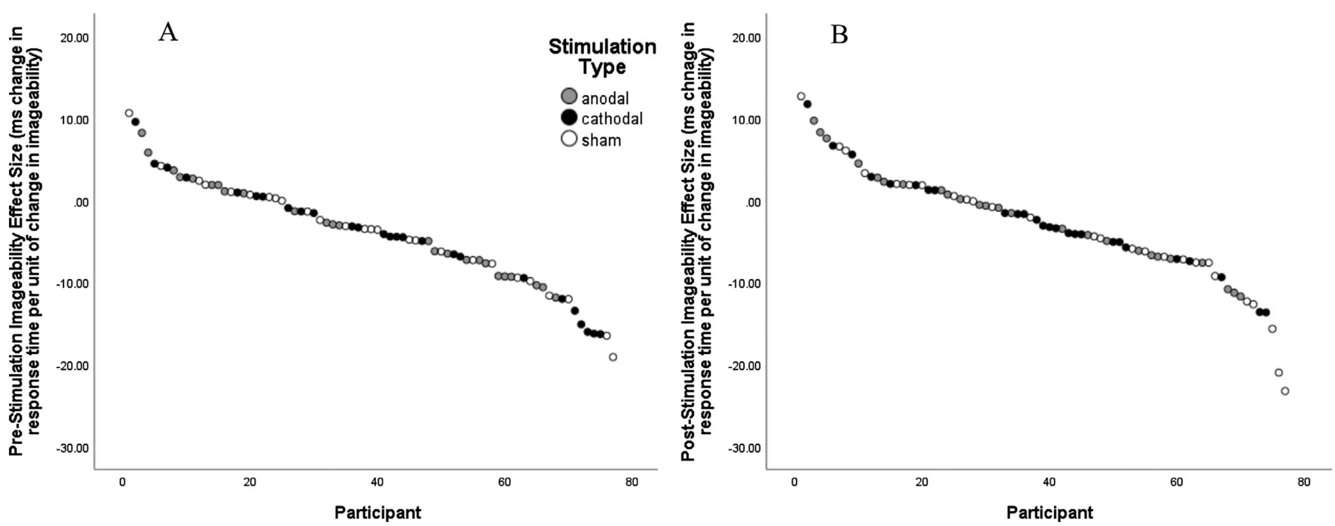

Fig. 2. A. Individual variability in the effect of imageability on response time at the pre-stimulation time point. B. Individual variability in the effect of imageability on response time at the post-stimulation time point.

Table 1
Mean (standard deviation) response times, imageability slope values and accuracy for each stimulation group. (*significant difference at corrected *p*-value).

		Pre-stimulation	Post-stimulation
Response time (ms)	Anodal	486.15 (67.98)	493.49 (80.34)
	Cathodal*	510.00 (76.02)	491.59 (65.28)
	Sham	523.79 (100.16)	522.37 (99.18)
Imageability slope values (rating/ms)	Anodal	−3.26 (5.72)	−1.81 (5.97)
	Cathodal	−4.69 (6.96)	−2.42 (5.74)
	Sham	−4.05 (6.54)	−4.33 (8.32)
Accuracy (%)	Anodal	90.78 (11.7)	92.12 (6.8)
	Cathodal	90.94 (11.7)	88.65 (14.8)
	Sham	92.83 (6.6)	89.59 (9.6)

decrease the role that imageability played in the facilitation of response time. In line with our hypotheses, the effects were greater for those individuals who were more sensitive to imageability effects pre-stimulation (i.e., greater slope values). Interestingly, the reduced imageability effect was found for both anodal and cathodal stimulation groups, which may indicate that any shifts to the baseline activity serve to alter the general reading network more broadly. No such effects were found for those individuals in the sham condition.

Importantly, stimulation did not broadly disrupt word reading times across all word types. Instead, the effect we observed for the active stimulation conditions was modulated by the magnitude of each individual's imageability effects in reading times, such that individuals who showed greater imageability effects pre-stimulation showed the greatest reduction in this effect post-stimulation. The specificity of this effect again provides evidence that stimulation to this region selectively influenced reading network pathways related to linking orthographic to semantic representations.

Just as importantly, stimulation to this region did not modulate performance on an N-back working memory task, which we included as a control task to assess the effect of stimulation on general verbal processing. The lack of an effect for this control task provides some evidence that the effect we observed for reading was not due to a generalized effect of stimulation on short-term memory, nor due to fatigue or other shared process. Rather, the specificity of the findings has important implications in the context of current models of word

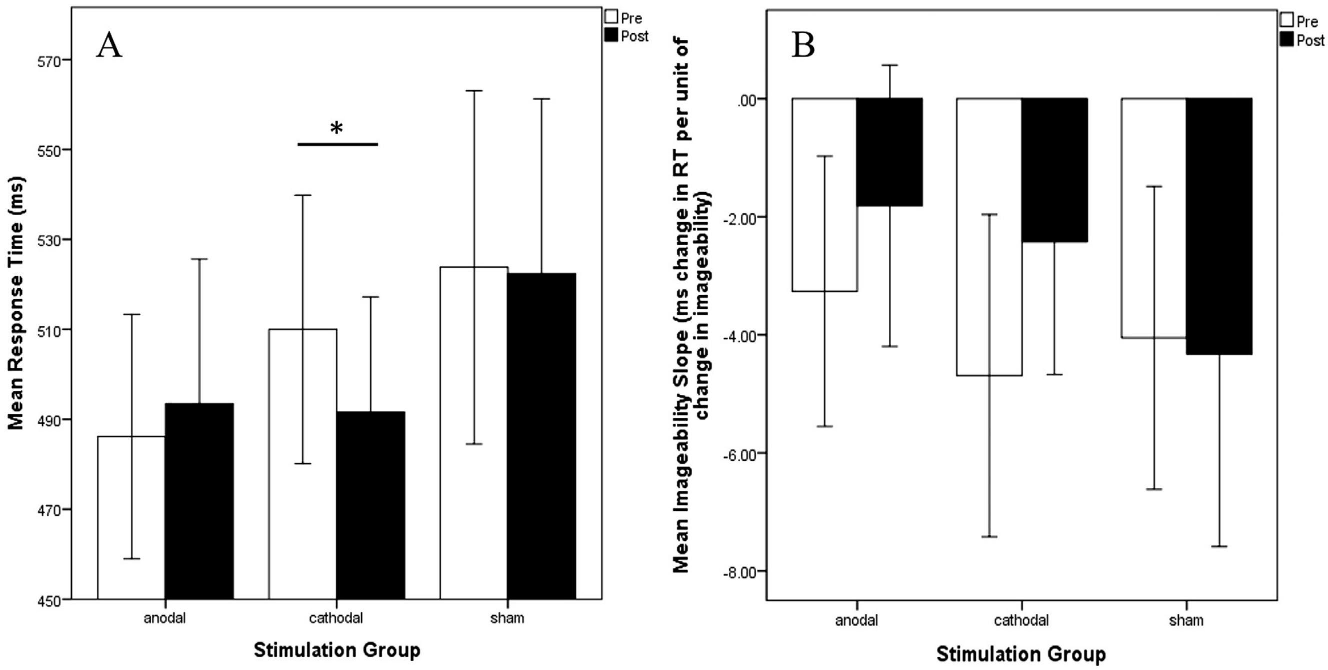

Fig. 3. Pre- and Post-Stimulation. (A) Mean Response Time and (B) Mean Imageability Slope Values, as a function of stimulation group. *Significant at $p < 0.01$. Error bars represent ± 2 standard errors.

recognition.

4.1. Facilitatory vs. Inhibitory effects of imageability

In line with previous work (Graves et al., 2014), we provide evidence for individual variability in reading aloud performance, whereby, approximately ⅔ of individuals show a facilitatory effect of imageability on RT and ⅓ show an inhibitory effect on RT. Active stimulation over the left angular gyrus served to decrease the impact of imageability on RT and this effect was magnified for individuals who were most sensitive to word imageability (i.e., large slopes when regressing word imageability ratings onto response times). Whereas there was no difference among the absolute change in imageability slopes across the three groups, the relationships between pre and post imageability slopes were different between active (anodal and cathodal) and sham groups. We propose that the generalized impact of stimulation was the result of disruption of semantic representations within an otherwise functioning reading network, effectively changing the balance of the contributions of representations associated with lexical/semantic and phonological/decompositional mechanisms that are engaged during reading. Whereas an exploration of shifts pertaining to individual variability in alternative representations (i.e., orthographic, phonological) is beyond the scope of the current work, several additional questions are raised. First, to what extent do alternative reading representations demonstrate comparable individual variability to the imageability effects examined here? Second, does such individual variability in slope scores shift in response to stimulation? Given that we utilized a single brain region here, we are limited in any claims we can make about the specificity of our findings to stimulation over the angular gyrus, and subsequent neighboring regions. Ultimately, disruption of the orthographic or phonological representations within the reading network, using a multisite, within subjects approach, is necessary to fully support our claim that modulation of the angular gyrus impacts semantic representations during reading. For now, the findings reported here provide one piece of the puzzle and we look forward to a more comprehensive description of the reading process as additional stimulation studies are conducted.

One important caveat here is the relatively weak spatial focality of the tDCS approach used in the present study. Whereas the intention of stimulation was to maximally target the angular gyrus via scalp electrode placement, spreading effects of the anodal/cathodal current could have stimulated other brain regions as well (see Fig. 1). Thus, the effect we observed here might have been due to inhibition or excitation to another nearby brain region. Similarly, the applied current may have instead served to modulate the connections between the supramarginal gyrus (SMG) and the angular gyrus (AG). In this case, increasing the connection between SMG and AG would have disrupted the connection between AG and pSTG that was initially the source of the faciliatory effects on RT (e.g., see Graves et al., 2014). Whereas Graves et al. did not explore the connections between AG and SMG and the resulting impact of such connections on RT, the results from our work suggest that further information is needed to understand how the interconnections among SMG and AG can impact reading aloud performance.

4.2. Modulating reading performance via brain stimulation

Over the last decade, there has been a growing body of literature in tDCS mediated research attempting to understand speech production and language networks (Lefebvre & Liew, 2017; Monti, et al., 2013). However, comparatively less work has been conducted to understand the impact of brain stimulation on reading performance and thus the current study adds to this accumulating literature base. The utilization of brain stimulation techniques are necessary to the advancement of neurobiological models of reading, as such approaches provide information about the disruption/facilitation of reading processes in a healthy population. Prior to the implementation of brain stimulation, what we knew about disrupted reading was primarily constrained to lesion based studies (Benson, 1981) and/or individuals with developmental reading disability (Castles & Coltheart, 1993). Now, we are afforded the opportunity to measure changes in reading performance in typical skilled readers to more fully understand the role of particular brain regions in the general reading network.

As we embark on this endeavour, we must consider the differences in techniques (e.g., TMS vs. tDCS) and the resulting impact on behavioural performance. For example, TMS is a brain stimulation approach

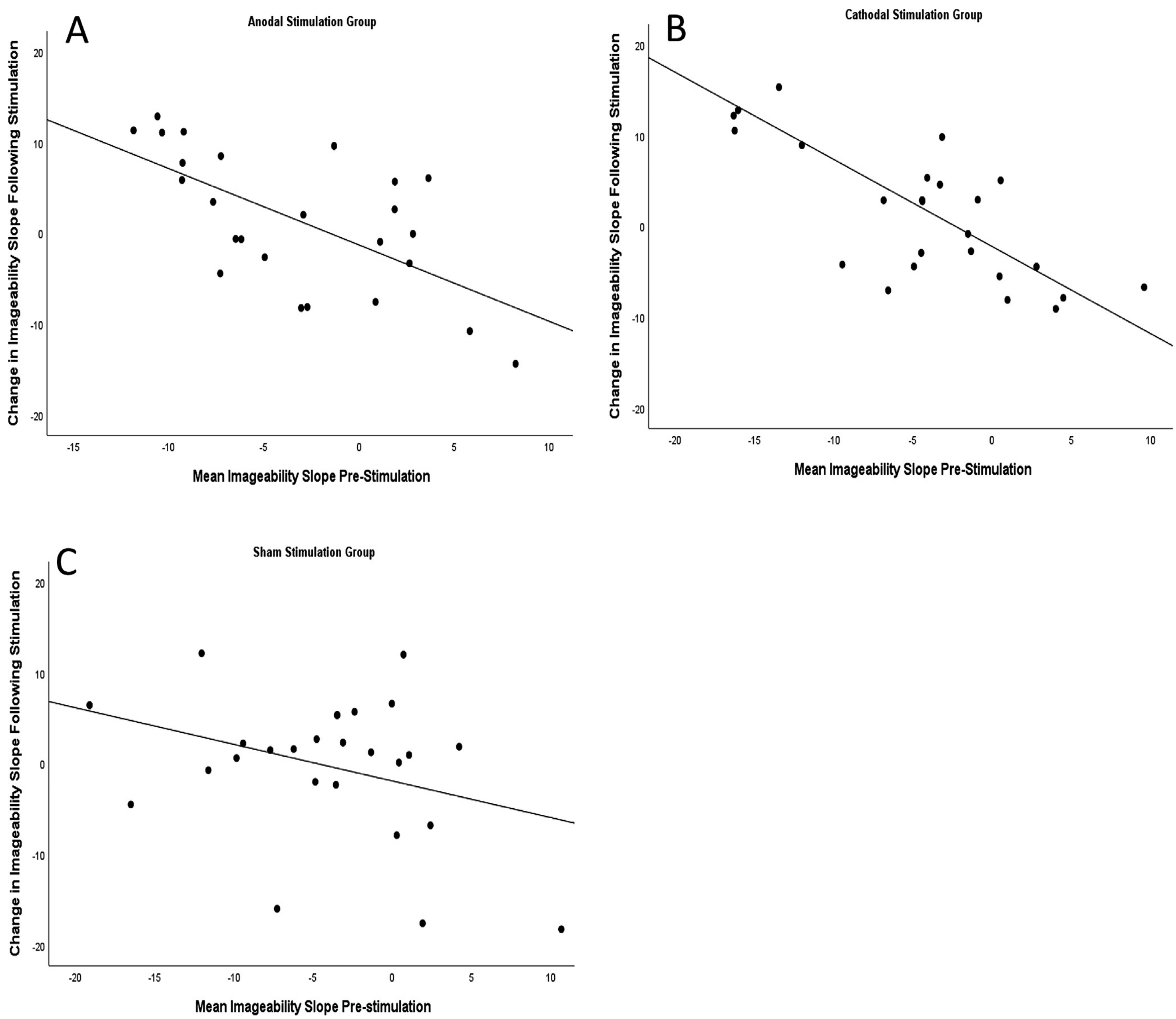

Fig. 4. The relationship between Mean Imeageability Slope Pre-Stimulation and Change in Imeageability Post-Stimulation for (A) Anodal ($p = 0.001$), (B) Cathodal ($p < 0.001$) and (C) Sham ($p > 0.05$).

that induces an action potential and actively modulates subsequent activity in a brain region. In contrast, tDCS does not induce an action potential, but instead changes the resting membrane potential making subsequent action potentials more or less likely (Nitsche, et al., 2003; 2008; Stagg & Nitsche, 2011). This important difference is illustrated in the findings by Sliwinska et al. (2015) who examined the impact of TMS on varying tasks and brain regions (i.e., supramarginal gyrus vs. angular gyrus) associated with phonological and semantic processes, respectively. The authors showed that the effect of TMS was to decrease behavioural performance localized to the task associated with the brain region being stimulated. Here, we explored the impact of varying active tDCS conditions (i.e., anodal vs. cathodal) on a single brain region for a task presumed to utilize the brain region targeted and a task not typically associated with the brain region targeted. In this case, the effect of modulating membrane potential of the angular gyrus up (anodal) or down (cathodal) had a similar negative impact on behavioural performance for the experimental task (naming words varying in imageability) but not for the task that did not require such information (N-back task).

Further, we need to be cautious when interpreting findings from studies that differ in design. For example, the current study utilized a single-blind approach. While we attempted to mitigate experimental bias by only assigning the coding of stimulation group after aggregation of data, the extent to which the experimental design inadvertently introduced bias is not fully known. This differs from Sliwinska et al. (2015), where there was no blinding as all participants were in all 'active' conditions. Our study focused on the presence/absence of stimulation effects during various tasks, whereas the latter focused on the role of stimulation to two brain regions during various tasks. In addition, the dynamic nature of the reading network is likely impacted by differences in task demands, whereby tasks might activate the same neural networks, but the level of activation may differ in relation to the specific task (Mechelli, Price, Noppeney, & Friston, 2003; Vogel, Petersen, & Schlaggar, 2013). Moreover, given that stimulation to one region can enhance one reading subskill while simultaneously weaken another, the employment of several reading tasks that tap into multiple sub skills is important to examine (Younger, Wagner, & Booth, 2016).

5. Conclusions

There are multiple pathways that support successful reading aloud. Here we provide the first evidence that the relative engagement of these pathways can be modulated in a way that shifts an individual's sensitivity to semantic characteristics, namely imageability. Clearly there is a need for additional work that explores the impact of tDCS on various regions in the reading network. To date, most studies have focused on the temporoparietal regions, including supramarginal and angular gyrus, while a handful of studies have also revealed changes in reading abilities following occipital and frontal lobe stimulation (Ashmore, R. A., Farrier, M. J., Paulson, L. H., & Chu, 2002; Heth & Lavidor, 2015; Pisoni, Papagno, & Cattaneo, 2012; Price, 2012). Ultimately, reading is a dynamic process that includes a complex network of brain regions and brain stimulation approaches will be useful to provide a more comprehensive understanding of the reading network.

6. Statement of significance

We examined an important language process, namely semantics (i.e., imageability), using a transient lesion approach (i.e., transcranial direct current stimulation). In line with the goals of *Brain and Language*, we used an interdisciplinary approach (i.e., experimental psychology and neuroscience) to assess the role of the angular gyrus in reading.

Declaration of interest

None.

Acknowledgments

This research was partially supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada in the form of a research grant to J Cummine (Discovery grant number: 386617-2012) CA Boliek (Discovery grant number: 312209-2013) and MF Joanisse (Discovery grant number 06018-2016). We thank Jessica Lammert for assistance in data acquisition.

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