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Title: Transcranial direct current stimulation improves novel word recall in healthy adults

Authors: Bre-Anna K. Owusu[1,2] & Hana Burianová[2,3]

[1]Department of Neuroscience, Centre for Advanced Research in Experimental and Applied Linguistics, McMaster University, Hamilton, Canada

[2]Department of Psychology, College of Human and Health Sciences, Swansea University, Swansea, Wales

[3]Centre for Advanced Imaging, University of Queensland, Brisbane, Australia

Correspondence should be addressed to:
Bre-Anna K. Owusu, MSc
Centre for Advanced Research in Experimental and Applied Linguistics
McMaster University
Hamilton, L8S 4K1, Canada
breannaroseking@gmail.com

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Abstract

Anodal transcranial direct current stimulation (atDCS) has demonstrated beneficial effects in the language domain for both healthy and brain damaged individuals. The present study provides evidence for the efficacy of atDCS in improvement of associative lexical learning in healthy adults, by employing a novel word-learning paradigm. Participants underwent single sessions of anodal and sham stimulation applied over the left posterior temporo-parietal junction, while learning ambiguous words paired with corresponding dominant, subordinate, and non-word meanings. The ability to recall each paired word was tested on a *Cued-Recall* task and the ability to recognize acquired non-words amongst distractors was tested using a *Recognition* task. The results revealed significant atDCS effects for non-word recall compared to sham stimulation in the *Cued-Recall* task, whilst average correct reaction times were not significantly different between stimulation conditions for the *Recognition* task. These results provide direct evidence that atDCS strengthens associative links produced between ambiguous words and non-words during initial word retrieval, indicating that these newly acquired words become integrated within participants' pre-existing linguistic experience. This study contributes important information on healthy language processing and highlights the efficacy of atDCS in improvement of language recovery in clinical domains.

Keywords: Ambiguity; Brain stimulation; Language processing; tDCS; Word learning

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1. Introduction

Lexical ambiguity is a ubiquitous phenomenon that can interrupt sentence comprehension, as listeners and readers must use contextual cues to access the suitable meaning for ambiguous words. Particularly in English, over 80% of common English words are known to have two or more distinct definitions (Rodd, Gaskell, & Marslen-Wilson, 2002). For example, the ambiguous word “punch” could represent a verb *(e.g., to strike someone with a forceful hit*), or a noun (*e.g., a cold fruit drink*). An important contributor to the disambiguation process is the relative frequency, or dominance, of an ambiguous word’s meaning (Rodd *et al*., 2013). For instance, the verb form of “punch” is considered its high-frequency (dominant) meaning, whereas the noun form is its low-frequency (subordinate) meaning. Twilley *et al*. (1994) demonstrated that, in the absence of context relevancy, participants were predisposed to retrieving the ambiguous word’s dominant meaning. Also, other studies have shown that an ambiguous word within a neutral context, in which either frequency meaning would be likely (*e.g.,* “The woman saw the punch…”), readers were biased towards the dominant frequency definition and showed particular difficulties when selecting a sole meaning for a balanced ambiguous word; a word with two equally frequent meanings (Rayner & Duffy, 1986).

In addition to meaning frequency biases, semantic relations can exist between a word with a single dominant meaning (*e.g.,* “ant”) and an attached fictional meaning. For instance, related/strong fictional meanings associated with a previously known word that has a single meaning are easier to recall in comparison to an unrelated/weak semantic relation between a word with a single meaning and its associated fictional meaning. Rodd *et al*. (2012) explored how adults acquired new meanings for words that contained a single meaning, by examining the role of semantic relatedness. Results demonstrated that strong semantic relations between novel and existing meanings significantly improved explicit memory recall of the new meanings compared to unrelated/weak semantic meanings. These findings led Rodd *et al*. (2012) to suggest that individuals integrate their pre-existing knowledge about the previously known word meaning with the newly learned meanings. However, studies have yet to investigate how adults acquire novel words associated with ambiguous words, in which a single word contains multiple meanings. This investigation could contribute informative language rehabilitation procedures for patient populations in the clinical domain.

Since ambiguous words are the most common (80%) in the English language, training them with non-words would demonstrate a more ecologically valid paradigm, rather than pairing them with a smaller sample of words (20%) containing sole meanings. Thus, if language impaired patients lose some of their vocabulary after a brain injury, it would be beneficial to incorporate language rehabilitative procedures using ambiguous words, as they form the majority of the English language. Furthermore, coupling this new word learning paradigm with brain stimulation may facilitate the strengthening of the paired associations between the ambiguous word and non-word/lost word. For this purpose, we investigated the role of associative relations between lexical ambiguity and novel word forms, using a new experimental paradigm and non-invasive brain stimulation (NIBS).

NIBS techniques, such as transcranial direct current stimulation (tDCS), have recently grown in popularity in hopes of enhancing neuroplasticity (Flöel & Cohen, 2010), the reorganization of dynamic structural and functional properties in the central nervous system (Pascual-Leone *et al*., 2005), and associated improvements in cognitive performance. tDCS applies weak electrical currents to the scalp, whilst modifying the excitability process of underlying cortical neurons (Nitsche *et al*., 2003). Facilitative effects on cognitive functioning have been reported with anodal transcranial direct stimulation (atDCS), whereby anodal stimulation enables firing of task-specific neurons (Kuo & Nitsche, 2012). To date, mechanisms underlying these facilitative effects remain highly disputed; however, some researchers propose that atDCS produces extended cortical excitation increments, which result from modifications to N-methyl-D-aspartate (NMDA) receptor connections known to be involved in long-term potentiation (Nitsche & Paulus, 2000, 2001). Furthermore, its effective placebo stimulation (sham tDCS) acts as a control or baseline state. Rather than modulating neural functions, sham tDCS elicits tingling sensations on the scalp, ensuring that participants are blind to the stimulation condition (Gandiga *et al*., 2006). Thus, combining tDCS with the novel word learning paradigm aids the investigation of stimulation's role in strengthening non-existent links between novel words and previously known ambiguous words, as well as contribute supplementary information regarding the facilitation of memory consolidation for these newly acquired lexical-semantic links.

In the language domain, numerous studies have demonstrated significant improvements in word-retrieval (Cattaneo, Pisoni, & Papagno, 2011; Meinzer *et al*., 2012, 2014a), vocabulary learning (Fiori *et al*., 2011), and lexical ambiguity processing (Peretz & Lavidor, 2013) when atDCS was administered over core language areas in the brain, such as left perisylvian cortices, left posterior temporo-parietal junction (TPJ), and right posterior TPJ, respectively. Based on these experiments and additional studies on post-stroke aphasic patients (de Aguiar, Paolazzi, & Miceli, 2015), suggestions regarding atDCS as an adjunct treatment for clinical populations have circulated. Specifically, it is suggested that studies with novel word learning paradigms in healthy individuals would aid in the optimisation of language re-learning in anomic patients (Basso *et al*., 2001), especially as tDCS permits the rare benefit of exploration of causal links between the brain and language processes, in contrast to other non-invasive methods, such as functional magnetic resonance imaging (fMRI) or electroencephalography. Here, we investigated whether atDCS would mediate the strengthening of the TPJ network that subserves novel word acquisition.

The aim of the study was to investigate the causal role of the left posterior TPJ in novel word acquisition using atDCS. This brain region has been found to play a significant role in new word learning in healthy individuals and post-stroke patients with language impairments (Cornelissen *et al*., 2003; Davis & Gaskell, 2009; Laine & Salmelin, 2010). To control for experiment induced artefacts, such as the placebo effect or sensitivity to stimulation, sham stimulation was implemented. Homonymous ambiguous words were trained with words corresponding to three levels of graded meaning frequencies; dominant, subordinate, and a non-word. For example, PUNCH-*fight* (dominant), PUNCH-*drink* (subordinate) and PUNCH-*fenct* (non-word). Participants' long-term memory was subsequently assessed using two tasks: a cued-recall memory test, which assessed ability to recall each word paired with the ambiguous word, and a recognition task, which assessed whether the non-words had become sufficiently well learned to affect speeded recognition of target non-words paired with distractor non-words. For the cued-recall task, hierarchical recall responses were expected; that is, we hypothesized that participants would recall dominant words more than subordinate words, and subordinate words more than non-words (Rodd *et al*., 2012, 2013). According to the complementary learning system (CLS), which assumes the ability to generalize familiar/trained mappings to novel items (Davis & Gaskell, 2009; French, 1999; McClosky & Cohen, 1989), we expected that the previously familiar mapping between the ambiguous word and its existing dominant and subordinate meanings would act as a complementary retrieval cue, aiding the recall of the non-word paired with the ambiguous word. Thus, we predicted that atDCS applied to the left posterior TPJ would significantly facilitate non-word recall compared to the control stimulation, in which atDCS reduces the amount of mapping interference that may occur during initial acquisition/training. Also, we expected that atDCS would *not* significantly aid in memory recall for dominant and subordinate meanings, compared to sham, since the existing mappings between the ambiguous word and the respective meanings have been strongly solidified via linguistic representations throughout the participants' lifetime, leaving little or no opportunity for atDCS strengthening. Lastly, based on studies, which have demonstrated that novel word forms can be rapidly learned after a few repetitions following consolidation (Dumay & Gaskell, 2007; Gaskell & Dumay, 2003), we expected that atDCS would decrease participants' reaction times during the recognition memory task and increase accuracy for recognition of target non-words compared to sham stimulation.

2. Methods

2.1. *Participants*

Twenty healthy participants were recruited from Swansea University's student pool. Four were excluded due to experimenter error and apparatus malfunction, for a total of sixteen participants (age range = 21-34; mean age = 24.25 years; SD = 2.96; 10 females) included in the analyses. All participants were native English speakers with normal or corrected-to-normal visual acuity, self-reported no colour-blindness and completed an exclusionary questionnaire, ensuring a history absent of neurologic, psychiatric, and systemic pathologies incompatible with tDCS (*e.g.*, epilepsy). All participants provided written informed consent, and upon study completion, participants were thanked for their participation and debriefed about the aims of the study, which was approved by the College of Human and Health Sciences Psychology Departmental Ethics Committee at Swansea University.

2.2. *Apparatus*

tDCS was delivered via battery-supplied direct current stimulators (HDCstim-DC stimulator, Magstim, Milano, Italy). Electrodes were inserted into synthetic sponges soaked in saline solution and secured to the scalp using a 10/20 BraiNet cap. The anode (4 x 4 cm) was positioned over the left posterior temporo-parietal junction (position Cp5) and the cathode (4 x 4 cm) was centred over the contralateral supraorbital region (position Fp2; see **Fig 1**). The positioning of electrodes was determined using the international 10-20 EEG system and though the sizing of electrodes were outside conventional protocol (5 x 5 cm / 5 x 7 cm), smaller and larger assemblies have been previously explored (Nitsche *et al.*, 2007).

[Insert Figure 1 here]

During atDCS, a constant direct current of 1.5 mA (0.09 mA/cm^2 current density) was administered throughout the acquisition phase, assuring that active stimulation was delivered for a total of 20 minutes whilst participants acquired the stimuli during the acquisition phase. The current increased and decreased in a ramp-like fashion over the first 10 seconds of stimulation and the last 10 seconds. The procedure during sham tDCS was identical to atDCS, except the current was turned off after the first 30 seconds of stimulation. Previous studies found significant cognitive benefits using this learning paradigm/electrode montage (Meinzer et al., 2012, 2014a). After completion of the acquisition phase during which participants underwent stimulation, electrodes were removed from participants' scalps prior to continuation of the filler task, recall phase and recognition phase.

Both computerised tasks (*Cued-Recall Memory* and *Recognition Memory*) were run on a Dell Intel Core2 OptiPlex 755 desktop CPU with a Dell E173FP 17" flat panel colour LCD monitor. All phases and participant responses were presented and collected via SuperLab 4.5.

2.3. *Stimulus Selection*

Forty ambiguous words with their dominant and subordinate word pairings were adopted from the study by Titone (1998) and used in the acquisition phase and cued-recall task during this study. Eighty pronounceable non-words were selected from Bangert, Abrams & Balota (2012): 40 of these were paired with ambiguous words whilst the remaining 40 served as untrained distractors during the recognition task. All non-words were in accordance with phono-tactic and orthographic rules of English. The mean length for non-words was 4.83 letters (*SD* = .84) and the mean orthographic neighbourhood (N) size was 3.63 (*SD* = 3.80; Coltheart *et al.*, 1977). Distractor non-words began with the same letter as its paired target word (*i.e.,* CARSH and COOD). Stimuli were divided evenly into two sets, counterbalanced, and rotated across individuals and stimulation conditions, respectively. All stimuli presented were lower cased.

2.4. *Learning Tasks and Performance Measures*

During the acquisition phase, word pairs appeared simultaneously on a blank screen for five seconds. This phase contained three randomized conditions (20 word pairs per condition). Condition I comprised ambiguous words paired with their dominant (D) meanings, condition II involved ambiguous words paired with their subordinate (S) meanings, and condition III consisted of ambiguous words paired with non-words (N). Each pair was presented alongside its corresponding 'condition letter' ("D", "S" or "N"; see **Fig 2A**). Pairs were presented randomly and repeated in four blocks (60 trials/block) without gaps. The duration of the acquisition phase was 20 minutes (60 trials, each lasting 5 seconds = 5 minutes/block, repeated 4 x = 20 minutes). Prior to commencing the acquisition phase, participants were briefed on the meanings of "D", "S" and "N" and were told to study and memorize all of the word pairs on the screen for later recall. During both *Cued-Recall* and *Recognition* tasks, the entire set of trained items were tested.

During the *Cued-Recall* task, a previously studied ambiguous word appeared on the screen along with letters "D" (dominant), "S" (subordinate), and "N" (non-word). Participants were instructed to recall the dominant, subordinate, and non-word paired with the ambiguous word shown via text in the box provided (20 trials; see **Fig 2B**), and were given unlimited time. Each trial was completed by clicking the "Next >" button on the screen.

In the *Recognition* task, participants were presented with two non-words (one previously studied target and one distractor) on the monitor simultaneously. Each non-word appeared either to the left or to the right of a centrally located fixation cross. Each non-word was assigned a key input from the keyboard and participants were instructed to produce fast, localized responses via keystrokes responding to the location of the target non-word. Thus, if the target non-word appeared on the left side of the screen, participants pressed ‘Q’, whereas if the target non-word appeared on the right side of the screen, participants pressed ‘P’ (see **Fig 2C**). The location of target non-words was counterbalanced and randomized across each participant.

[Insert Figure 2 here]

2.5. *Design and Procedure*

A sham-controlled, single-blinded, within-participants factorial design was employed with factors stimulation type (anodal vs. sham) and meaning frequency (dominant vs. subordinate vs. non-word). The dependent variables were the percentage of correct responses (CRs) for the *Cued-Recall* task and the average reaction times (RTs) alongside percentage accuracy for the *Recognition* task. Testing occurred in a quiet laboratory compartment in Swansea University, with participants seated approximately 100 cm from the computer monitor with a 19.2° full monitor width viewing angle. This experiment involved an acquisition, distractor, and test phase. Each stimulation session was carried out between 10 a.m. and 6 p.m., and a gap amid 7 and 14 days between each stimulation condition was implemented to control for learning and carry-over effects (Nitsche *et al*., 2008). The order of anodal and sham stimulation was counterbalanced across participants. Also, an equal number of participants were randomized to the sham versus the anodal condition first.

All participants completed the tDCS Screening Questionnaire prior to study participation. This questionnaire excluded participants from the study who were incompatible with tDCS. After screening was completed, participants were briefed on session goals and sat in front of the computer monitor with electrodes attached to their scalps. Stimulation commenced upon presentation of the first word pair in the acquisition phase and stopped after the presentation of the last word. Participants were monitored for adverse tDCS side effects, such as the presence/absence of headaches, neck pain, scalp pain/burns, or tingling. Directly after the acquisition phase, the experimenter removed the electrodes and instructed participants to complete the tDCS Side Effects Questionnaire, which determines the presence and severity of various sensations known to occur during tDCS, such as tingling (Nitsche *et al*., 2008). Subsequently, an unrelated filler task was administered, whereby participants typed into a text box as many countries as they could think of in three minutes. The purpose of the filler task was to prevent covert rehearsal of word pairs before the final test phase.

Following the three-minute gap, the test phase began with the *Cued-Recall* task. During this task, trained ambiguous words were presented randomly in the middle of the screen, sequentially, in addition to condition letters “D”, “S”, and “N”. Participants were instructed to recall the correct dominant, subordinate, and non-word previously paired with the ambiguous word in the acquisition phase, via text response in a box located to the left of the condition letters. Participants pressed ‘Enter’ to begin a new line and clicked “Next>” to proceed to following trials. Spelling was considered and participants were instructed to make estimates if unsure of the correct word/non-word response. Raters implemented an all-or-nothing scoring scheme regarding incorrectly spelled words. There were 20 trials in one block without interruptions. This task took approximately 5 minutes to complete.

In the *Recognition* task, participants viewed two non-words (distractor and target), simultaneously presented on the screen, and pressed ‘Q’ as fast as possible when a target non-word appeared on the left side of the screen or ‘P’ when a target non-word appeared on the right side of the screen. A fixation cross (500 msec) appeared in the centre of the screen before each trial. The non-word pairs appeared until the participant responded with a key press. There were 20 trials in one block. This task took approximately 1 minute to complete. The tDCS Side Effects Questionnaire was completed again 24 hours post each session and participants were debriefed after the second session. Results were not given after either session.

3. Results

3.1. *Self-Report Measure*

All participants included in the analyses tolerated atDCS and sham stimulation well, with minimal adverse side effects. **Table 1** summarizes the reported tDCS adverse side effects data for each group across sub-categories. Tingling was the most common side effect reported during atDCS, while sleepiness was commonly reported amongst participants undergoing sham stimulation. Paired *t*-tests yielded non-significant results for total adverse side effect ratings in each group (anodal: M = 11.50, SD = 1.93 vs. sham: M = 11.75, SD = 2.44, $t(15) = .43$, p = .67), demonstrating a lack of differences in overall adverse side effects during stimulation sessions.

[Insert Table 1 here]

3.2. *Cued-Recall Task*

A 3 x 2 repeated measures ANOVA on accuracy with factors meaning frequency (dominant vs. subordinate vs. non-word) and stimulation type (anodal vs. sham) revealed a significant main effect of Meaning Frequency [$F(2,30) = 22.37$, $p < .001$, $\eta p^2 = .60$] and a significant interaction of Meaning Frequency and Stimulation Type ($F(2,30) = 78.58$, $p < .001$, $\eta p^2 = .84$; see **Fig 3**). Main effect of Stimulation Type was not significant ($p = .86$). These results suggest that the level of accuracy when recalling dominant, subordinate, and non-words depended on the type of stimulation received during the acquisition phase.

[Insert Figure 3 here]

Mean cued-recall accuracies for correct word responses and standard deviations between stimulation and sham conditions are shown in **Table 2**. *Post hoc* comparisons with Tukey's corrections using paired *t*-tests revealed non-significant differences in accuracy between sham and stimulation for dominant cued-recall ($t(15) = -.46$, $p = .66$) and subordinate cued-recall ($t(15) = 1.95$, $p = .07$). However, participants showed a significant difference for non-word cued-recall accuracy ($t(15) = 2.20$, $p = .04$), demonstrating that atDCS facilitated participants' recall memory for non-words compared to sham.

Moreover, the percentages of correct word recall in both stimulation conditions demonstrated that dominant words were recalled more than subordinate words and subordinate words were recalled more than non-words (**Table 2**). *Post hoc* analyses using paired *t*-tests showed that participants were more accurate when recalling dominant words compared to non-words in both conditions (sham: $M = 62.50$, $SD = 21.76$, $t(15) = <.001$; anodal: $M = 48.75$, $SD = 28.84$, $t(15) = <.001$), and similarly when recalling subordinate words versus non-words (sham: $M = 49.38$, $SD = 22.43$, $t(15) = <.001$; anodal: $M = 46.88$, $SD = 23.51$, $t(15) = <.001$). Also, paired *t*-tests revealed that participants were significantly more accurate when recalling dominant words compared to subordinate words; however, only in the sham condition (sham: $M = 13.13$, $SD = 10.63$, $t(15) = <.001$; anodal: $M = 1.88$, $SD = 10.78$, $t(15) = .50$).

[Insert Table 2 here]

3.3. *Recognition Task*

Paired *t*-tests were used to assess overall recognition percentage accuracies and average RT differences on accurate trials for non-words between sham and stimulation conditions. Participants showed higher overall percentage accuracies for recognizing target non-words from distractors in the stimulation condition compared to sham; however, differences were not significant (sham: $M = 92.19$, $SD = 12.91$ vs. anodal: $M = 95.63$, $SD = 7.50$, $t(15) = 1.17$, $p = .26$; see **Fig 4**). Similarly, although participants had faster average RTs (msec) on accurate trials during stimulation compared to sham (anodal: $M = 1278.23$, $SD = 344.13$ vs. sham: $M = 1306.42$, $SD = 303.82$, $t(15) = -.47$, $p = .64$; see **Fig 5**), these differences were not significant.

[Insert Figures 4 & 5 here]

4. Discussion

The aim of this study was to develop a novel word learning paradigm and utilize it to assess the effects of atDCS on language learning. The paradigm was designed to effectively invoke lexical-semantic links between previously known ambiguous words and non-words, with objective measures of recall accuracy and memory recognition RTs following a brief exposure to stimulation. To achieve this, we implemented a hierarchical training approach, in which dominant, subordinate, and non-word meanings were trained randomly with a corresponding ambiguous word. Unlike Rodd *et al.*'s (2012) experiment, which trained fictional meanings with sole dominant meaning words, our task consisted of homonymous ambiguous words (*i.e.,* words with multiple meanings) to which participants memorized and attached a novel word meaning. An important feature of the paradigm is the ability to accurately measure recall and recognition performance by comparing correct responses and average RTs, respectively, under two stimulation conditions. The benefits of gauging accuracy under two different stimulation conditions in this experiment are threefold: (i) to attain a measure of meaning frequency under both stimulation conditions, providing supplemental information about the significance of 'dominance' in ambiguous word learning; (ii) to provide causal links between the stimulated target region (left posterior TPJ) and new word learning; and (iii) to increase speeded recognition of target non-words, which reflects the effects of atDCS in memory consolidation.

This study demonstrated that the participants' ability to recall familiar meanings (dominant and subordinate) for homonymous ambiguous words during both stimulation conditions was significantly better than their ability to recall novel words paired with the same ambiguous words in either condition. This dominance effect was strikingly large; for instance, participants were only able to recall 20% of novel words, as compared to 82% of dominant word meanings and 69% of subordinate word meanings when their brains were not stimulated. The overall low performances for non-word recall may have been a result of short-term priming effects on novel traces, as successful lexical priming relies on modifying pre-existing mappings of memory or acquiring novel memory traces (Bowers, 1994). For example, when a familiar ambiguous word is presented for the first time within the experiment, it would activate its permanent pre-existing representation in the participant's lexicon and the activation may endure long enough, so that accessing the representation upon subsequent presentations would become easier (McKone & Trynes, 1999). Contrastingly, when non-words are presented with a lexically ambiguous prime, pre-existing representations are unavailable for modification and thus no priming results; hence, a low overall performance score for non-word recall. Alternatively, the acquisition theory denotes that the few non-words that are accurately recalled may be a result of new episode-specific memory traces that are generated from the initial presentation of the non-word. Thus, the priming of certain non-words results in participants' reusing the training processing strategies at test for cued-recall of the acquired memory trace (Jacoby, 1983; Roediger, 1990), demonstrating that priming can extend to unfamiliar stimuli.

We also found a significant difference between stimulation types (*i.e.,* anodal and sham stimulation) only for non-word recall, suggesting that when the left posterior TPJ is stimulated, participants are better able to recall non-words as opposed to when this brain region is not stimulated. Since lexical-semantic links for novel words were non-existing, our results demonstrate that stimulation to the TPJ was the driving factor in strengthening of the newly formed associations. Together with participants' responses for dominant, subordinate, and non-word recall across the two stimulation conditions, the results provide strong support that the pre-existing lexical semantic relationships between the ambiguous words and their equivalent dominant and subordinate meanings have been strongly mapped in participants' linguistic experience, such that stimulation did not play a role in further strengthening the associative links between the familiar ambiguous words and their meanings. Thus, newly acquired words became integrated within the participants' pre-existing knowledge of the ambiguous words and their corresponding meaning frequencies (*i.e.*, dominant and subordinate).

Unexpected results regarding non-word recognition RTs were observed. On average, participants were faster at selecting the correct non-word from alternative distractors in the stimulation condition; however, this trend did not reach significance. A possibility for this occurrence stems from a phenomenon known as lexical dissociation. Previous studies of word form learning showed that the initial retrieval of information for novel words may dissociate from latter consolidation into the lexicon, despite the words being rapidly learned after multiple presentations (Rodd *et al*., 2012). For example, the non-word "*fenct*" can be dissociated from the associative impact in recognizing the existing word "*fence*" during lexical decision tasks, until consolidation has occurred. Similarly, the process of consolidation between the ambiguous prime and non-word may have not yet been completed after a single training session to procure significant RT differences. Thus, if participants failed to integrate the non-words into their existing lexical knowledge, albeit via lexical association, their recognition and recall responses would depend solely on their pre-existing lexical representation of the non-word, which would not exist.

Overall, the current findings replicated previously documented atDCS facilitative effects (Fiori *et al*., 2011; Flöel *et al*., 2008; Meinzer *et al*., 2014a) demonstrating a significant difference for novel word recall compared to sham stimulation, when applied to the left posterior TPJ. However, a few limitations regarding the stimulation of the target site in this study need to be acknowledged. First, the left posterior TPJ overlaps Wernicke's area, a brain region thought to be responsible for word production and phonological retrieval processes (Davis & Gaskell, 2009). Additional areas, such as the dorsal inferior frontal cortex and the inferior parietal lobule have also been implicated in the aforementioned processes (Laine & Salmelin, 2010), and due to the moderately large size of electrodes used in this experiment, known distant effects of atDCS on these functionally relevant areas could have also been present. Therefore, a higher current density in mA/cm^2 (*i.e.*, smaller electrode sizes) may reduce the dispersal of the electric current via electrodes (anode to cathode) to neighbouring, functionally related brain regions, resulting in a more concentrated current focused on the target site. Second, although previous studies show strong evidence that language processing is strongly left lateralized in both sexes for right handed individuals (Chai *et al*., 2016; Frost *et al*., 1999), it cannot be completely ruled out that the cathode positioned over the right hemisphere contributed to the facilitating effect.

5. Conclusions

The presence of a lexical-semantic link between non-words and ambiguous words may critically depend on the participants' experience with these words during training/acquisition, such that integration of these non-words into the pre-existing linguistic network emerges only once training has been successful. Thereby, our findings suggest that atDCS applied over the left posterior temporo-parietal junction improves novel word recall in healthy individuals and contributes important and novel information concerning the potential beneficial effects that non-invasive brain stimulation might have on therapeutic interventions in language recovery for clinical populations. While this study implemented a novel word learning paradigm, using stimulation as a mediator of stronger linguistic encoding, future studies can investigate this model further, using complementary functional imaging, in which concurrent application of tDCS with fMRI will allow for the exploration of neural mechanisms underpinning behavioural tDCS effects, due to the high spatial resolution images produced across the brain (Meinzer *et al*., 2014b). This technique will identify stimulation induced brain activity modulations at the target stimulation site and in distant brain areas aforementioned that are associated with task-related functional behavioural improvements.

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Figure Captions

FIG 1. Depiction of Electrode Positions. The illustration demonstrates a bilateral placement of the electrodes based on the EEG 10-20 system. ‘A’ (red) represents the placement of the anode over position Cp5 (TPJ) and ‘C’ (black) demonstrates the fixed position of the cathode over position Fp2 (contralateral supraorbital region). Significance in all figures is denoted by ‘*’.

FIG 2. Study Overview. Study overview. (A) Demonstrates the structure of the acquisition phase. Participants sat in front of a monitor and were instructed to view and memorize word pairs with the corresponding ‘condition letter’ for subsequent tasks. (B) Illustrates the cued-recall memory task. An ambiguous word was presented and participants had to recall from memory the correct word for each condition letter. (C) Highlights the design of the recognition memory task. Participants saw a fixation cross followed by two non-words. Participants chose which non-word they previously studied in the acquisition phase via keystrokes. Since ‘CARSH’ was the target non-word and appears on the right side of the screen, participants were to press the letter ‘P’ on the keyboard. Trials ended with a fixation cross indicating the start of a new one.

FIG 3. Mean percentages of cued-recall accuracy and standard deviations for anodal (light grey) and sham (dark grey) stimulation for each of the meaning frequency conditions (dominant vs. subordinate vs. non-word).

Fig 4. Mean overall recognition accuracy for selecting target non-words from paired non-word distractors and standard deviation bars for anodal (light grey) and sham (dark grey) stimulation.

Fig 5. Mean average correct reaction times (in msec) on accurate trials for target non-word recognition, and standard deviation bars for anodal (light grey) and sham (dark grey) stimulation.

Tables

Table 1: ***Means and standard deviations for adverse event rating sub-categories on tDCS Side Effects Questionnaire (1 = absent, 2 = mild, 3 = moderate, 4 = severe; p-values based on paired t-tests).***

	atDCS[a]		Sham[b]		*p*-value
	M	*SD*	*M*	*SD*	
Headache	1.19	.54	1.25	.58	.58
Neck Pain	1.06	.25	1.25	.58	.08
Scalp Pain	1.06	.25	1.06	.25	1.00
Scalp Burns	1.13	.34	1.00	.00	.16
Tingling	1.81	.66	1.44	.51	.03
Skin Redness	1.06	.25	1.00	.00	.33
Sleepiness	1.56	.73	2.00	.89	.05
Trouble Concentrating	1.31	.60	1.69	.79	.08
Acute Mood Change	1.31	.70	1.06	.25	.16

[a] *n* = 16.
[b] *n* = 16.

Abbreviations: **atDCS** = anodal transcranial direct current stimulation.

Table 2: ***Mean cued-recall accuracy (in %) and standard deviations as a function of meaning frequency based on post-hoc comparisons.***

	atDCS[a]		Sham[b]	
	M	*SD*	*M*	*SD*
CR Dominant	80.63	14.25	82.19	16.12
CR Subordinate	78.75	16.18	69.06	23.82
CR Non-word	31.87	24.55	19.69	20.85

[a] *n* = 16.
[b] *n* = 16.

Abbreviations: **atDCS** = anodal transcranial direct current stimulation hemisphere; **CR** = correct response.