Enhancing Resolution of Ambiguous Words with Brain Stimulation to left IFG: a tDCS study of Hebrew

The role of left IFG in selection and suppression meanings of homographs: a brain stimulation (tDCS) study

# Introduction

## Models of ambiguous word processing

Readers often come across an ambiguous word (homograph) that refers to several semantic representations. For example, the homograph *bank* has the meaning of *money* or *river*. Such a word may challenge readers when they are required to choose the appropriate semantic representation. Studies show that the course of processing and selection is influenced by two main factors: the context and the dominance of meaning (Duffy et al., 1988; Peleg et al., 2010; Peleg & Eviatar, 2008; Giora, 2003). The context directs the readers to one of the meanings, thus helping to make a quick decision and expedite the processing. For example, in the sentence *The fisherman sat on the – bank* the context directs to the meaning *river*, and it will be chosen by the readers (Van Petten & Kutas, 1990; Van Petten & Kutas, 1991). The second factor, the dominance of meaning, depends on the reader's previous experience with the word, which makes one meaning more common or familiar. The relationship between the homograph and the common (dominant) meaning is stronger than it is with the less common (subordinate) meaning, and accordingly, the process of activation and selection of this meaning is more effective (Peleg et al., 2001).

Various models have been proposed to describe the selection process (for details see Giora, 2003; Van Petten, 2002; Simpson, 1984; Burgess & Simpson, 1988). According to the exhaustive access model (Fodor, 1983), the processing of ambiguous words is done in two stages. First, all the meanings of the words are activated, and then the one that is appropriate for the context is selected, while rejecting the other meanings. This model assumes that the activation phase is performed by a modular lexical mechanism that is not sensitive to dominance or context. After activation and word processing, selection is made based on dominance and / or context. The selection process is therefore post-lexical (Onifer & Swinney, 1981; Swinney, 1979). Other models assume that dominance and context have an immediate effect, however they disagree about the relative weight of each. On the one hand, the selective access / direct access model assumes that a strong connection can guide the retrieval process, so that only the appropriate meaning will arise. This model assumes an interactive mechanism by which processes of activation, integration, and selection occur in parallel and influence each other. According to this single-stage model, when a context is strongly directed towards one of the meanings, a decision will be made even before the lexical retrieval stage, regardless of the prevalence of the different meanings (Gibbs, 1994; Martin et al., 1999; Vu et al., 2000). On the other hand, hybrid models such as the reordered access model or the graded salience hypothesis (Giora, 1997, 2003) assume that there is an exhaustive retrieval but the degree of activation of each meaning depends on its dominance - the more common the meaning, the faster its retrieval. In addition, intentional context can accelerate the retrieval of the appropriate meaning, but will not delay retrieval of other meanings. Thus, if the previous context tends towards the secondary meaning, it will strengthen the activation of it but will not inhibit the arousal of the dominant meaning. In such a case, the conflict between the two meanings will delay the selection process. In contrast, if the relevant meaning is dominant, the selection process will be shorter because this meaning will receive double reinforcement (Duffy et al., 1988; Colbert-Getz & Cook, 2013; Binder & Rayner, 1998; Giora, 2003; Peleg et al., 2001; 2008). According to this approach, the dominance component may help or complicate the selection process: if the relevant meaning is dominant, the selection process will be effective. If the relevant meaning is the subordinate, the dominant meaning will interfere with the selection process because it will delay the activation of the secondary meaning.

## Types of ambiguity

A closer look at the properties of the homographs shows that two main groups can be identified: a homophonic homograph (identical spelling: *bank*; identical pronunciation: /bank/) and a heterophonic homograph (identical spelling: *tear*; different pronunciation: /tIər/, /tεər/). The homophonic homograph has only semantic ambiguity (what is the relevant meaning of the word: *money* / *river*). In the heterophonic homograph there is both semantic (what is the relevant meaning: *crying* / *rip*) and phonological ambiguity (what is the relevant pronunciation). Most previous studies on ambiguous words have focused only on semantic ambiguity and the effect of context and frequency on the process of choosing the appropriate meaning. In the written Hebrew alphabetic language, unlike Indo-European languages, the vowels are not marked, and therefore heterophones are more common in it, and this is the language used in this study. Does the addition of phonological ambiguity change the process of selecting the relevant meaning? A comparison between these two types of homographs makes it possible to examine whether the selection process in this case is either related to more initial stages (phonological ambiguity) or to higher processing stages (semantic ambiguity). If similar findings are obtained among the homographs, the findings may indicate that the process is primarily semantic, while a difference between them may suggest a phonological effect.

One of the studies that investigated the two types of homographs and also compared them in terms of brain functions is that of Peleg & Eviatar (2009). Their research objectives were based on previous findings which showed that word processing was characterized by several paths in an orthography-phonology-semantics connection. One path is the conversion of orthography to phonology and phonology to semantics, and is focused on the left hemisphere, whereas the other path is a direct conversion of orthography to semantics operating in both hemispheres (Lavidor & Ellis, 2003; Smolka & Eviatar, 2006; Zaidel & Peters, 1981). They wanted to examine these connections with respect to both types of homographs. Their finding showed that there was a difference in the left hemisphere in the processing of the homographs. Presentation of a homophonic homograph to the left hemisphere resulted in activation of both the dominant and subordinate meaning, whereas displaying of a heterophonic homograph evoked only the dominant meaning. The findings may suggest that in the left hemisphere the decision in the case of heterophonic homographs may be made at an earlier stage, only on the basis of phonological information. In contrast, on the right hemisphere there was no difference between the homographs, and this is consistent with previous studies (Burgess & Simpson, 1988; Chiarello et al., 1990; Beeman et al., 1994).

Another step in examining the processing differences between these two homographs was done in an fMRI study by Bitan et al. (2017). They sought to examine the neural circuits involved in processing both types of homographs, and whether the model according to which semantic ambiguity (homophonic homographs) is processed in both brain hemispheres but phonological ambiguity (heterophonic homographs) in the left hemisphere (Peleg & Eviatar, 2008; 2012) can be validated. Their study was divided into two stages. In the first phase, participants were presented with ambiguous words - homophonic or heterophonic homographs, without context - and the hemispheric pattern of action was examined. In the second stage, the homographs were flashed again, but were followed by target words, referring to the dominant or subordinate meaning, in order to follow the hemispheric activity when encountering context.

The findings from the first phase indicated a functional difference between processing of homophonic (*bank*) versus heterophonic homograph (*tear*). In condition with homophonic homograph bilateral activity in the anterior IFG (pars orbitalis) was shown whereas in heterophonic homograph there was activity on the left side only - in the posterior IFG (pars opercularis; BA 44) - alongside a reduction in activity in the anterior IFG. The interpretation given to this was that the bilateral activity in the anterior IFG reflected a process of semantic decision when presenting a homophone. In this process all the meanings arise, but the dominant one is chosen. Further studies have indicated that this is a region of semantic selection (Moss et al., 2005; Vigneau et al., 2006). The activity in left posterior IFG (posterior LIFG), observed during heterophonic decoding, reflected a decision-making process at the phonological level (Bitan et al., 2005; Wheat et al., 2010) because in heterophonic stimulation the decision also includes a phonological dimension. Moreover, in the heterophonic homograph, reduced activity was observed in the anterior IFG, and this was attributed to the fact that in the absence of context, the decision (in the direction of the dominant meaning) was already made at the phonological level. The researchers attributed the activity observed to the process of deciding between different options, rather than to preserving the options. If it were an active holding of two (or more) options, we should have seen evidence of the activity of semantic holding in both types of homographs, because both have dual semantic representation. The activity at the semantic level was observed mainly in homophone, while in heterophone the activity was in a different region and mainly reflected the phonological level.

Also in the second stage (context stage) functional differences were found between processing of homophonic and heterophonic homographs. The salient findings relate to the conditions of subordinate meaning. In the heterophonic homograph (*tear*), there was increased activity in the posterior LIFG in the subordinate meaning (*rip*), compared to the dominant (*crying*), and the researchers believe this reflected the difficulty in detaching from the dominant phonological representation chosen in the first stage (replacing /tIər/ with /tεər/). Similarly, in the homophonic homograph (*bank*) there was more activity in the condition of subordinate meaning (*river*), in bilateral anterior IFG. This activity reflected the difficulty of detaching from the dominant meaning chosen in the first stage (exchanging *money* for *river*).

The research findings of Bitan et al., (2017) may contribute to the research discussion on the question of the role of posterior LIFG. There are several approaches that address this question, among them the general versus the specific approaches. Some proponents of the general approach argue that IFG is part of a left frontal region that focuses on regulatory processes and working memory, and all cognitive and verbal skills attributed to the anterior region can be explained through regulatory and working memory features (Thompson-Schill et al., 2005). Another general approach is that of Rodd et al., (2010) that IFG is a general area of ​​choice because it has been reported to be involved in selection processes in the semantic, phonological, and syntactic realms. The other approach argues that targeted regions can be identified within IFG, and they specialize in specific functions (see details in Clos, 2013). The imaging study of Bitan et al., (2017) shows that two regions with different functions can be distinguished. The posterior area of LIFG, pars opercularis, is involved in phonological selection, whereas the anterior region pars orbitalis (and its homologous counterpart) is involved in semantic selection. In the present study we will continue to examine the role of posterior LIFG and see to which approach the findings will be more appropriate.

## Non-invasive electrical brain stimulation

Another brain test to examine the differences in the resolution of semantic ambiguity between homophonic and heterophonic homograph can be performed using non-invasive electrical brain stimulation. This technique is called transcranial Direct Current Stimulation (tDCS), and it has become common in recent decades. It involves short-term discharge of a weak electric current on the scalp over target areas in the brain. The currents reach the cortex, and according to their polarity they can either induce (anodal current) or inhibit (cathodal current) activity (for more information: Priori, 2003; Fregni & Pascual-Leone, 2007; Nitsche et al., 2008; Utz et al., 2010; Hamilton et al., 2011). After/during the stimulation a task is performed, and according to a comparison between the experimental and control groups it is possible to check what the stimulation effect is and to infer the nature of the involvement of the stimulated area. Stimulation studies done on word processing have found an improvement in functioning in a variety of aspects. With respect to the semantic aspect, it was found that response times were improved in a semantic judgment task with homophonic homographs (Ihara et al., 2014) or in performing a semantic blocked naming task (Pisoni, et al., 2012). In terms of pragmatic processing, a faster response was observed in identifying expressions in which pragmatics are violated (Osovlanski & Mashal, 2017). In terms of syntactic processing, electrical stimulation has led to an improvement in the detection of syntactic errors in artificial language (De Vries et al., 2010) or in real language (Sakai et al., 2002). In the phonological aspect, an improvement in the performance of a task involving phonological working memory has been documented (Berglund-Barraza et al., 2020) as well as an increase in the ability to learn and acquire sound sequences (Savill et al., 2015). When no change is seen in the performance of tasks, a possible conclusion is that the target area is not involved in the process (Yankovitz & Mashal, 2020).

Few stimulation studies have examined the posterior LIFG region with reference to phonological processing. One of the phonological functions examined is the identification of differences in a string of sounds (Sehm et al., 2013). The participants were given pairs of words with identical phonetic and orthographic components except for one difference (e.g., Tisch-Fisch) in a variety of challenging auditory states. They had to decide whether they had heard two identical or different phonological sequences. The findings showed that training in combination stimulation in left IFG significantly increased performance in distinguishing between word pairs compared to sham group. In contrast, stimulation in the IPC region did not improve performance.

In other situations of two challenging phonological sequences, involvement of the left IFG was also found. In a stimulation study using TMS (Nixon et al., 2004) a task of matching words according to sounds and a task of matching pictures were given. It was found that stimulation in the left IFG changed performance only phonologically but not visually. In a follow-up experiment in which only a phonological adjustment was made, again changes were shown in the stimulation group versus control group. Similar data emerge from another study of stimulation with TMS (Gough et al., 2005) that included a task of semantic decision (whether there is a semantic relationship between words) and a phonological decision (whether words rhyme). All participants performed the two tasks twice, once as part of an electrical stimulation to the posterior LIFG region and once more to the anterior LIFG. A double dissociation was found between the stimulation areas and the type of task so that posterior LIFG stimulation created a change in the performance of the phonological rather than semantic task, whereas anterior LIFG stimulation created a change in the performance of the semantic rather than phonological task.

Another phonological function affected by electrical stimulation is the phonemic fluence. In this task the participant is required to say aloud as many words beginning with a given phoneme (Kavé, 2005). In a tDCS stimulation study on posterior LIFG (Iyer et al., 2005) with two phases, one excitatory and one inhibitory, inverse effects were found. The phonemic fluence increased when the stimulation was excitatory, but there was a decrease in performance with inhibitory stimulation.

Following on from these studies, and in line with the findings from the imaging study on the involvement of posterior LIFG in the phonological processing of heterophonic homographs (Bitan et al., 2017), we sought to examine using brain stimulation to the posterior LIFG region possible phonological effects in resolving semantic ambiguity. As far as is known, no stimulation study has been performed on this brain area in homographic word processing. The research task focused on the selection process when resolving semantic ambiguity, a process in which the appropriate meaning of the homograph is selected, while suppressing the inappropriate meaning. To this end, the study used a semantic task that requires the suppression of the irrelevant meaning of an ambiguous word (Gernsbacher & Faust, 1991). As part of the assignment, participants were asked to read sentences and decide whether a target word presented immediately after reading the sentence was related to the meaning of the sentence or not. The sentences ended with polar ambiguous words (one meaning is more common than the other) and the context pointed to the less common meaning of the ambiguous word (for example, *The fisherman sat on the - bank*). The target word presented after the sentence, has always been related to the dominant irrelevant meaning (e.g., *money*). For each ambiguous sentence (*The fisherman sat on the bank*) a control sentence was constructed that was identical to the sentence on the ambiguous condition except for the ambiguous word (*bank*) which was replaced by unambiguous one (*river*). In both conditions, the target word was unrelated to the meaning of the sentence (the correct answer was "no"). The difference (in terms of response time and accuracy) between the ambiguous (*The fisherman sat on the - bank - money*) and the unambiguous condition (*The fisherman sat on the - river - money*) indicates the intensity of the disturbance of the irrelevant meaning. That is, the more difficult the decision-making process (the more difficult the selection of the subordinate meaning / suppression of the dominant meaning), the greater the difference between the unambiguous control conditions and the ambiguous conditions (in terms of response times and accuracy). The objectives of the study are: (1) To investigate the process of semantic selection by comparing a homophonic homograph and a heterophonic homograph. The homographs will be presented to the participants as a part of a task that ensures a process of selection in the relevant meaning. (2) To examine the role of posterior LIFG in the selection process. The study of Bitan et al. (2017) showed that there is activity in this region when processing heterophonic homograph, and here we want to examine whether electrical stimulation will improve the selection process.

# Experiment 1

## Method

**Participants**

Twenty-two undergraduate students (13 women, 9 men), aged 21–31 (mean age 24.8 SD 2.6) participated in the study. They were all healthy, native speakers of Hebrew with normal or corrected to normal vision. Thirty additional participants, from the same population, were recruited for the pretests for the development of the stimuli.

**Stimuli**

The experimental materials consisted of 40 noun–noun polarized Hebrew homographs (20 homophonic and 20 heterophonic). The list of homophonic homographs was balanced with the list of heterophonic homographs for frequency, polarity, and length. The frequency was measured by using the Frost online archive (The Word-Frequency Database for Printed Hebrew), and in T test no significant difference (*p*>0.4) between the lists was found. The polarity (the distance in salience between the first two meanings) was checked by a pretest. Fifteen participants were presented with homographs and their paraphrased meanings and were instructed to indicate the frequency of each one of the meanings of a given homograph on a 1–10 scale. The average score of each meaning across participants served as the salience score for that meaning. For each homograph, the meaning with the highest and second highest salience scores were collected, and these served as the dominant and subordinate meanings, respectively. The gap between the two scores served as the polarity index. After comparing the lists with T test there was no significant difference (*p*>0.6). The measure of length was based on the number of letters for each homograph, and again, there was no significant difference in T test (*p*>0.7) between the lists.

For each homograph, a sentence context, with length of three to six words, was constructed (*The fisherman sat on the*), preceding the final homograph (*bank*). The sentence context was biased toward the subordinate meaning. A word that was related to the dominant meaning and was unambiguous, was selected, and served as a target word (*money*). Participants were asked to decide whether the target word was related to the sentence meaning. The correct answer was NO. The control condition was built in the same pattern, with one difference: the prime word was unambiguous (*The fisherman sat on the – river – money*). In this condition the answer was NO, as well. In order to balance the answers with YES, filler sentences were constructed, in which the primes were semantically related to the targets (e.g., *The fisherman sat on the – river – water*). The semantic relatedness between the sentence context and the final homograph (experiment condition) was balanced with the semantic relatedness between the sentence context and the final unambiguous word (control condition) by a pretest. Fifteen participants were presented with the sentences and their final words and rated the relatedness on a 1–10 scale. In T test no significant difference (*p*>0.4) between the lists was found. The target words were not balanced.

Table 1

*Examples of stimuli.*

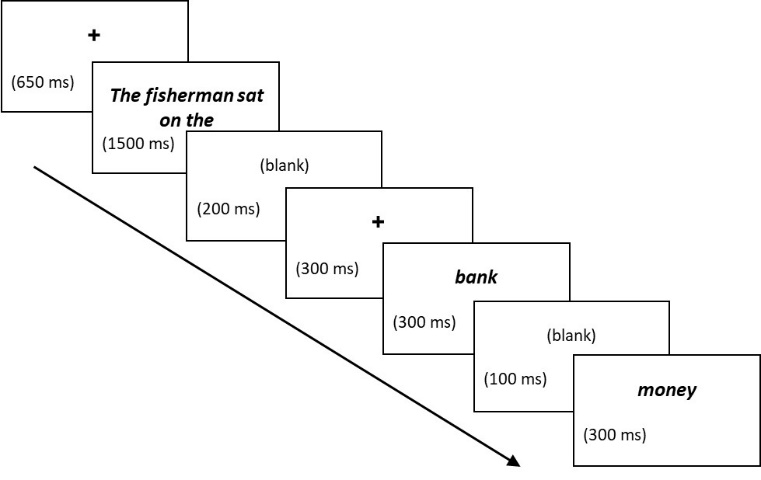
|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Condition** | **sentence context** | **prime** | **target** | **answer** | **stimuli** |
|  | experiment | *The fisherman sat on the* | *bank* | *money* | no | 20 |
| homophonic homograph | control | *The fisherman sat on the* | *river* | *money* | no | 20 |
|  | filler | *The fisherman sat on the* | *bank* | *water* | yes | 40 |
|  | experiment | *In her dress was a* | *tear* | *crying* | no | 20 |
| heterophonic homograph | control | *In her dress was a* | *belt* | *crying* | no | 20 |
|  | filler | *In her dress was a* | *tear* | *rip* | yes | 40 |

**Task**

Selection of relevant meaning task: Participants made a semantic relatedness judgment task with selection of relevant, subordinate meaning of homograph (Gernsbacher & Faust, 1991; Gernsbacher & John, 2001). Specifically, the task demanded suppression of a dominant meaning while selecting the subordinate. Participants were presented with the biased sentence and its final homograph (*The fisherman sat on the – bank*) and were asked to decide whether the target word (*money*) was related to the sentence meaning. By selecting the answer NO, they suppressed the auto-retrieved, dominant meaning (*money*) of the homograph (*bank*).

**Procedure**

The first part of the study included gathering personal information and signing consent form that was approved by the local ethic committee (school of education, Bar-Ilan University, Israel). Then, the task was given. Each trial began with a central fixation marker presented for 650 ms followed by a sentential context (i.e., the sentence without the final homograph: *The fisherman sat on the*), that was presented in the center of the screen for 1500 ms. The offset of the sentence was followed by a 200 ms blank period and a central fixation marker for 300 ms. Then, the homographic prime (*bank*) was presented in the same central position for 300 ms. At 100 ms ISI (400 ms SOA), the target word (*money*) was presented in the center for 300 ms. Participants indicated whether the two words were related or not by pressing B/N buttons with the index or middle finger of their right hand, respectively (See figure 1).



*Figure 1*. Time course of experiment.

Stimuli presentation and responses were controlled and recorded by an HP 13.3 i3 laptop. The distance from the computer screen was 60 cm. Stimuli, constructed from characters presented in Ariel font (size 20), were colored black and displayed on a white colored screen. The study was programmed using SuperLab© software (version 5.0).

The effect of each homograph was calculated as the difference (in terms of response time and accuracy) between the experimental conditions and their controls.

## Results

A 2 x 2 ANOVA for repeated measures was conducted on RTs and error data separately with homograph type (homophonic/heterophonic homograph) and ambiguity (ambiguous/unambiguous word) as within-subject factors. Mean RT, SDs and error rate in all conditions are given in Table 2.

Table 2. Mean RTs and percent of error and SDs.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Homograph** | **N** | **ambiguous** | **unambiguous** |
| RT | heterophone | 22 | 1154.54 (248.21) | 1037.68 (188.07) |
| homophone | 22 | 1097.19 (196.12) | 1039.83 (188.38) |
| ERR | heterophone | 22 | 12.88 (12.29) | 4.79 (6.92) |
| homophone | 22 | 12.62 (5.47) | 10.60 (5.11) |

*Reaction Times*

The main effect of ambiguity was significant (F(1,21)=23.25, *p*<.001, ηp²=0.52), with longer RTs to ambiguous words (M=1125.86, SD=222.16) than control, unambiguous words (M=1038.76, SD=188.22). The main effect of homograph type was not significant (F(1,21)=2.43, *p*>.05, ηp²=0.10). The ambiguity X homograph type interaction was significant (F(1,21)=6.09, *p*<.05, ηp²=0.23). T tests revealed longer RTs for heterophonic than homophonic homograph (t(21)=2.52, *p*<.05), but not for control conditions (t(21)=0.10, *p*>.05). In addition, RTs of both heterophonic (t(21)=5.86, *p*<.005) and homophonic (t(21)=2.45, *p*<.05) homographs were greater than their control.

*Percent of Error*

The main effect of ambiguity was significant (F(1,21)=22.04, *p*<.001, ηp²=0.51), revealing higher percentage of errors for ambiguous words (M=12.75, SD=8.89) than control, unambiguous words (M=7.71, SD=6.01). The main effect of homograph type was not significant (F(1,21)=2.62, *p*>.05, ηp²=0.11), however, the ambiguity X homograph type interaction was significant (F(1,21)=4.92, *p*<.05, ηp²=0.19). T tests showed higher percentage of errors for heterophonic homograph than its control (t(21)=3.75, *p*<.005), but not in the homophonic condition (t(21)=1.70, *p*>.05). See figure 2.

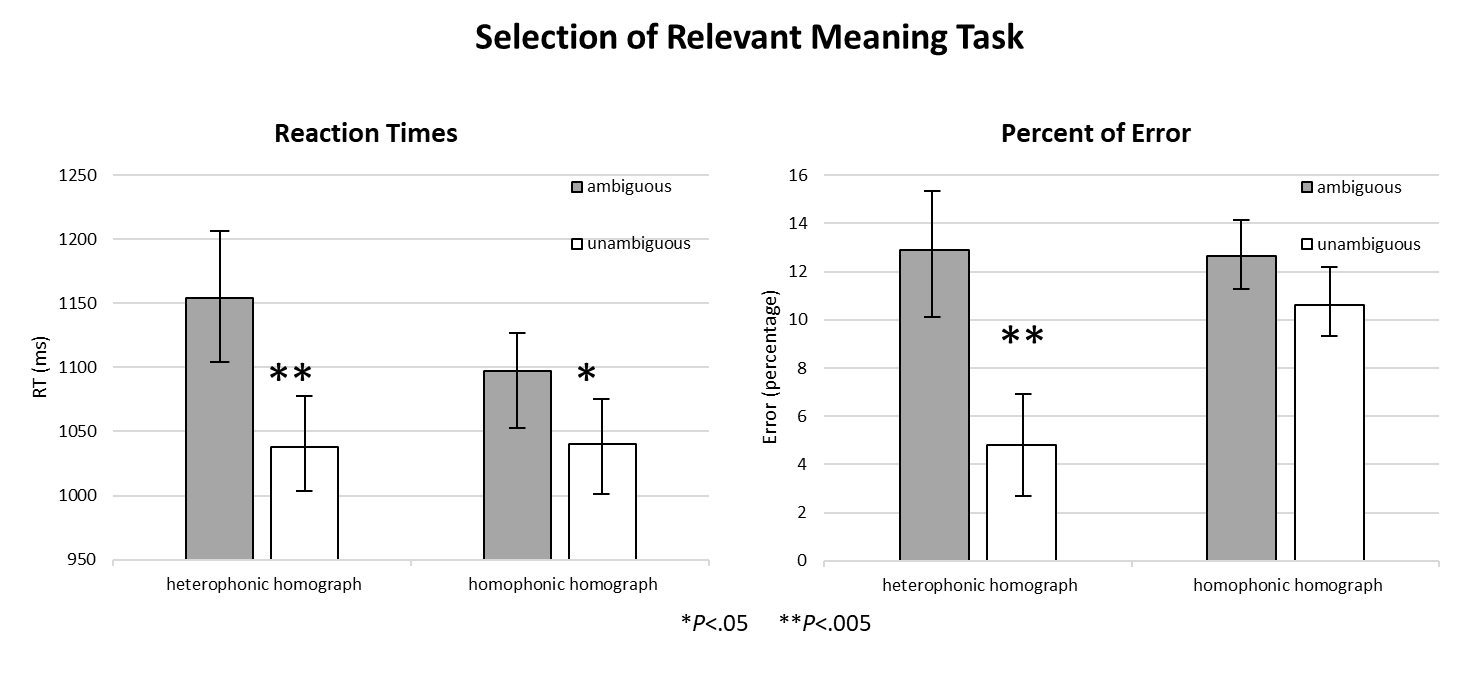


Figure 2. Mean RTs and percent of error and SEs.

## Discussion

The aim of this experiment was to examine whether the process of selecting the subordinate meaning of heterophonic homograph would be more difficult due to the addition of phonological ambiguity. By comparing heterophonic homograph (two semantic representations and two phonological representations) with homophonic homograph (two semantic representations and one phonological representation) it was possible to isolate the element of phonological ambiguity and examine it.

It has been found that an ambiguous word is generally more difficult to process, as shows the main effect. Furthermore, the significant interaction suggests that ambiguity effect (the difference between ambiguous and unambiguous conditions) varies between the homographs. Referring to homophonic homograph, choosing the subordinate meaning while suppressing the dominant (Gernsbacher & Faust, 1991; Gernsbacher & John, 2001) was involve in an increase in response times and error rates, indicating difficulty, compare to unequivocal word (without any ambiguity). This effect was reported also in previous studies (Rayner and Duffy, 1986; Rayner et al., 1994; Rodd et al., 2005; Ihara et al., 2007).

When phonological ambiguity (under heterophonic conditions) was added, the task of suppressing dominant meaning became even more complex, and this seems to be attributed to the fact that suppression of dominant meaning also required suppression of dominant phonological representation. The context in the sentence led the participant to decode the prime word *tear* according to the subordinate meaning (/tεər/), but previous experience with the homograph also resulted in an automatic activation of the dominant meaning associated with another phonological representation /tIər/. The significant lengthening of response times may indicate that there have been automated processes of orthography-phonology mapping in the dominant meaning, so that the homograph *tear* automatically evoked the phonological representation (/tIər/), making it difficult for the participant to choose the subordinate meaning. These findings concur with the findings of divided visual field studies (Peleg & Eviatar, 2009) that show an immediate selection in the dominant phonological representation when the homograph is presented without a biased context; And with the findings from the imaging study of Bitan et al. (2017) who showed difficulty in processing homographs especially when the context pointed towards the subordinate. In addition, these studies have shown differences in the processing of both types of homographs in the left hemisphere (Peleg & Eviatar, 2009) and more specifically in the left IFG (Bitan et al., 2017). In the study by Bitan et al, in the heterophonic condition, there was more activity attributed to the phonological area (posterior LIFG) whereas in the region attributed to semantic decision (bilateral anterior IFG) the activity was almost normal. Taken together, these findings suggest automated phonological activity during heterophonic homograph processing.

# Experiment 2

## Method

**Participants**

Twenty-four undergraduate students (8 women, 16 men), aged 21–28 (mean age 24.1 SD 1.7) participated in the study. They were all healthy, native speakers of Hebrew with normal or corrected to normal vision, and did not participate in the first experiment. They were tested with Wechsler vocabulary scale, Hebrew version (Wechsler, 2008). Participants were divided into two groups, experiment (active stimulation) and placebo (sham). In the active group were thirteen participants (4 women, 9 men), aged 21–28 (mean age 24.6 SD 1.9). Their Wechsler’s mean score was 14.9 (SD=1.4). In the sham group were eleven participants (4 women, 7 men), aged 21–25 (mean age 23.4 SD 1.2). Their Wechsler’s mean score was 14.4 (SD=1.4). There was no significant difference between the groups either in age (t(22)=1.71, *p*>.05), gender distribution (χ2(1)=0.54, *p*>.05) or vocabulary knowledge (t(22)=0.99, *p*>.05). All participants confirmed that they were healthy, did not suffer from epilepsy, did not carry any metal in their head, did not use pacemaker, did not report any addiction to drugs or alcohol and did not use psychiatric drugs.

**Stimuli**

Materials and task were the same as those used in experiment 1.

**Procedure**

Each participant took part either in active (active stimulation) or sham group (placebo-like stimulation) randomly. The first part of the study included gathering personal information and signing consent form. Then, tDCS stimulation was administered (either active or sham). At the end of the session the selection of relevant meaning task of experiment 1 was given.

tDCS (1.5 mA) was administered for 15-min through two saline-soaked sponge electrodes (5 × 5 cm), using a constant current stimulator (neuroConn DC stimulator plus, Incl GmbH). The anode electrode was placed on posterior LIFG (pars opercularis, corresponding to Broadman 44. see Bitan et al., 2017) and the cathode electrode positioned on the contralateral orbita. Posterior LIFG was located according to the crossing point between T3-Fz and F7-Cz (de Aguiar et al., 2015; Cattaneo et al., 2011) using the 10–20 EEG system (Monti et al., 2008; Pisoni et al, 2017). Participants were blinded to stimulation type.

## Results

One participant suffered from headache for 72 hours after active tDCS. The rest tolerated the stimulation well and no adverse effects were demonstrated. All participants completed both tDCS sessions (active, sham) and all accompanying tasks.

A 2 x 2 x 2 ANOVA for Repeated measures – mixed design was conducted on RTs and error data separately with stimulation group (active/sham) as between-subject factor, and with homograph type (homophonic/heterophonic homograph) and ambiguity (ambiguous/unambiguous) as within-subject factors. Mean RT, SDs and error rate in all conditions are given in Table 3.

*Table 3*. Mean RTs and percent of error and SDs.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Group** | **homograph** | **N** | **ambiguous** | **unambiguous** |
| RT | heterophone | active | 13 | 1091.16 (187.61) | 1073.74 (193.32) |
| sham | 11 | 1169.22 (203.24) | 1044.37 (191.03) |
| homophone | active | 13 | 1110.89 (234.93) | 1004.72 (187.63) |
| sham | 11 | 1053.09 (247.25) | 1003.15 (221.40) |
| ERR | heterophone | active | 13 | 10.77 (13.04) | 3.08 (3.25) |
| sham | 11 | 10.00 (7.41) | 2.73 (3.48) |
| homophone | active | 13 | 9.95 (8.45) | 6.33 (7.38) |
| sham | 11 | 10.69 (7.81) | 5.88 (3.72) |

*Reaction Times*

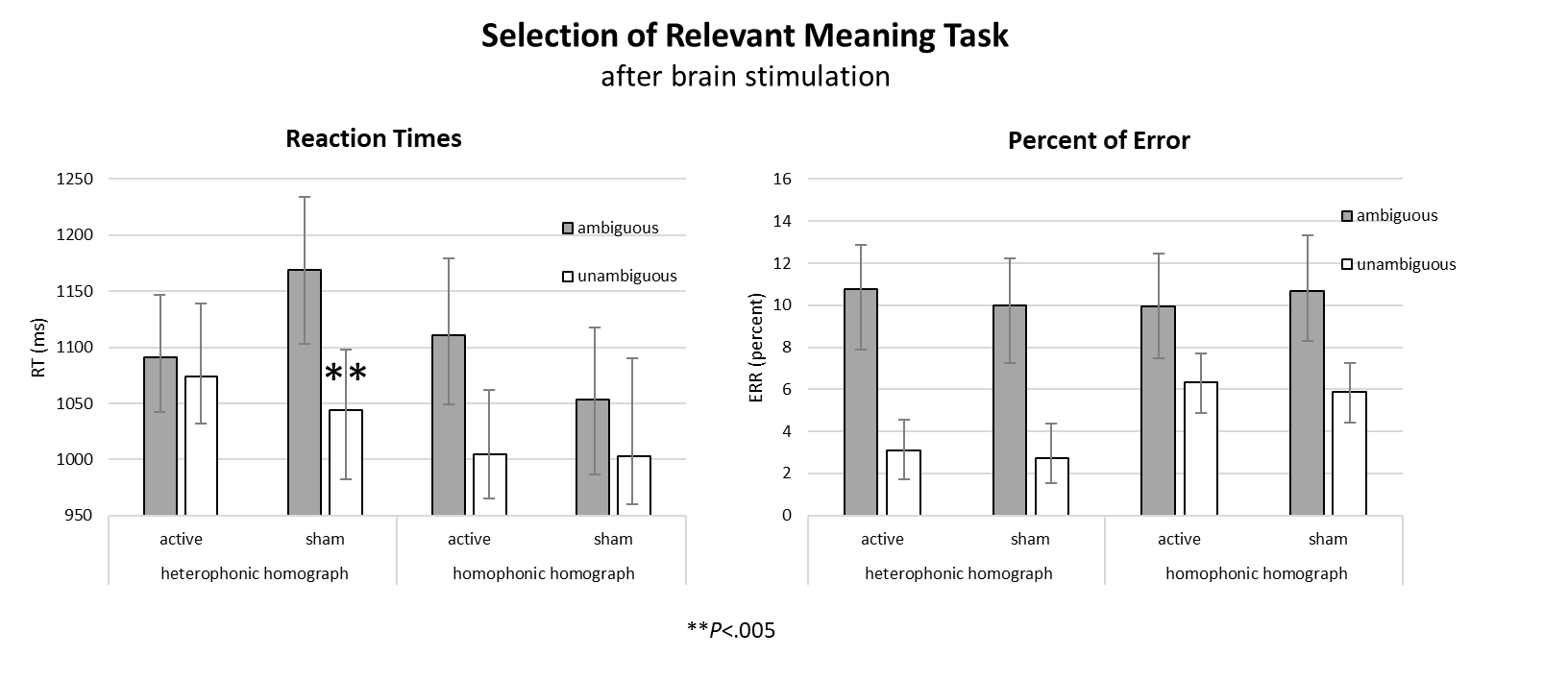
The main effect of ambiguity was significant (F(1,22)=23.12, *p*<.001, ηp²=0.52), with longer RTs to ambiguous words (M=1106.09, SD=215.91) than control, unambiguous words (M=1031.49, SD=191.53). There was also a significant main effect of homograph type (F(1,22)=10.30, *p*<.005, ηp²=0.32) with longer RTs to heterophones (M=1094.62, SD=191.66) than homophones (M=1042.96, SD=215.78), but no main effect of stimulation group (F(1,22)=0.01, *p*>.05, ηp²=0.0). The three-way interaction of brain stimulation X homograph X ambiguity was significant (F(1,22)=5.98, *p*<.05, ηp²=0.21). To break down this interaction, two ANOVAs were performed, one for each type of homograph.

For heterophonic homograph, a 2 x 2 mixed design ANOVA was conducted, with stimulation group (active/sham) as between-subject factor, and ambiguity (ambiguous/unambiguous) as within-subject factor. There was a main effect for ambiguity (F(1,22)=12.05, *p*<.005, ηp²=0.35), showing slower RTs to heterophonic homograph (M=1126.93, SD=194.68) than control, unambiguous words (M=1060.27, SD=188.65). No main effect for stimulation group was found (F(1,22)=0.10, *p*>.05, ηp²=0.01), but the two-way interaction of stimulation group X ambiguity was significant (F(1,22)=6.86, *p*<.05, ηp²=0.24), indicating that ambiguity effect (ambiguous-unambiguous) of heterophonic homograph was affected differently by tDCS. T tests revealed slower RTs for ambiguous versus unambiguous condition in sham group (t(10)=4.35, *p*<.005), but similar RTs (ambiguous-unambiguous) in active group (t(12)=0.60, *p*>.05), suggesting that the active stimulation reduced the ambiguity effect (See figure 3).

For homophonic homograph, a 2 x 2 mixed design ANOVA was conducted, with stimulation group (active/sham) as between-subject factor, and ambiguity (ambiguous/unambiguous) as within-subject factor. There was a main effect for ambiguity (F(1,22)=9.81, *p*<.01, ηp²=0.31) with slower RTs to homophonic homograph (M=1084.40, SD=237.15) than the control condition (M=1004.01, SD=194.42). There was no main effect for brain stimulation (F(1,22)=0.12, *p*>.05, ηp²=0.01). No interaction was found (F(1,22)=1.27, *p*>.05, ηp²=0.05) indicating that the ambiguous condition’s performance of homophonic homograph was not affected by brain stimulation.

*Percent of Error*

The main effect of ambiguity was significant (F(1,22)=10.62, *p*<.005, ηp²=0.32) and demonstrates that the rate of errors in the ambiguous condition (M=10.35, SD=9.25) of the suppression task was higher than the control condition (M=4.51, SD=4.50) (unambiguous word). There was no significant main effect either for homograph type (F(1,22)=1.58, *p*>.05, ηp²=0.22) or brain stimulation (F(1,22)=0.10, *p*>.05, ηp²=0.0). There were no significant interactions. The absent of interactions suggested that tDCS did not affect the rate of error in both types of homographs.



*Figure 3*. Mean RTs and percent of error and SEs. Only one interaction was significant, in RT of heterophonic homograph (ambiguity x stimulation).

## discussion

The aim of this experiment was to examine whether posterior LIFG region is involved in selection between either phonological or semantic competing representations of subordinate and dominant meaning when processing ambiguous words. The main finding was an improvement in reaction times of the phonological ambiguity conditions and a lack of change with semantic ambiguity. The findings have implications for understanding the role of LIFG in homographic word processing.

The left IFG region has been described in many studies as a neural network associated with phonological function, both in imaging and in stimulation studies. There are imaging studies in which activity in this area was reported when decision between competing phonological representations was made (Bitan et al., 2017; Matsuo et al., 2010) and when general phonological function was performed (Opitz et al., 2003; Braun et al., 2015). Various stimulation studies have also shown that there is an improvement in functions related to phonological components in word processing (Sehm et al., 2013; Nixon et al., 2004; Gough et al., 2005).

Further to these findings is the current stimulation experiment in which the phonological function examined is the selection between two competing representations, referring to the subordinate and the dominant meaning of a homograph. During the task the subordinate meaning should be chosen while delaying and rejecting the dominant. The comparison between heterophonic homograph (identical spelling: *tear*; different pronunciation: /tIər/, /tεər/) and homophonic homograph (identical spelling: *bank*; identical pronunciation: /bank/) made it possible to isolate the element of phonological ambiguity and examine it. The significant interaction stimulation x homograph indicated that in the sham group there was a significant difference in response times when the task included the phonological ambiguity component, beyond the semantic ambiguity. This gap is attributed to orthography-phonology mapping processes that have become more difficult, compared to the condition of homophonic homograph. In the task, each step began with a sentence context *In her dress was a* that led the reader to decode the prime word *tear* according to the subordinate meaning (/tεər/). During the transition from the prime to the target word *crying*, the dominant meaning *tear =* /tIər/ arose. Had there been equality between heterophonic and homophonic homographs, it could be said that the phonological ambiguity was already resolved in the initial sounds of the word (distinction between /tε/ and /tI/). The significant lengthening of response times may indicate that there have been automated processes of orthography-phonology mapping in the irrelevant dominant meaning, so that the entire phonological representation has arisen (/tIər/), making it difficult for the reader to reject it and choose the subordinate meaning. In contrast, in the active group the response time was significantly shortened so that there was no difference between the homographs. That is, the electrical stimulation eliminated the phonological ambiguity effect. Posterior LIFG, as an area of ​​choice between phonological representations (Bitan et al., 2017; Matsuo et al., 2010; Nixon et al., 2004; Gough et al., 2005), received excitation through stimulation, which led to efficiency and speed in suppressing phonological representation of the irrelevant dominant meaning (/tIər/). In terms of response times, a significant average improvement of about 90 ms was found in performing the task. The result is consistent with previous stimulation studies (Sehm et al., 2013; Nixon et al., 2004; Gough et al., 2005) that found an improvement in phonological function.

Interpretation of these findings may be reinforced by a stimulation study with TMS (Aziz-Zadeh et al., 2005) aimed at inhibiting the left IFG region and examining its implications for silent and vocal reading in ordinary words. Voice reading requires orthography-phonology mapping. The study examined whether the mapping also takes place in silent reading ("Activation of the inner speech"). The findings showed that both voice and silent reading had a delay. The researchers concluded that even in silent reading, automated orthography-phonology mapping processes work, and can be suppressed through inhibitory stimulation. Imaging studies have also found that IFG is involved in inner speech processes (Baciu et al., 1999; Perrone-Bertolotti et al., 2012; Ashby, 2016).

Regarding the percentage of errors, it was found that there was no improvement in the active group compared to the sham. That is, the stimulation showed an effect on processing speed in conditions with phonological ambiguity, but not on accuracy. It is possible that the accuracy was in ceiling effect and it was not possible to reveal an improvement in the accuracy component.

Another key finding in the present study is the performance results under the condition of semantic ambiguity. This ambiguity was tested using the gap between the homophonic homograph and its control condition (unequivocal word). Here it was found that there was no improvement between active and sham groups. This finding was predictable because semantic activity is distributed in several areas of the brain. According to Bitan et al., (2017), the activity of semantic decision in IFG is bilateral and in the more anterior regions, and according to Zempleni et al., (2007), parallel activity in temporal parts (MTG, ITG) was also observed. It is evident, then, that semantic activity is more decentralized than phonological, and targeted electrical stimulation to left IFG does not contribute. Reinforcement for this conclusion comes from the study by Pisoni, et al., (2012) where excitatory tDCS stimulation enhanced semantic effect when the target area was STG, and less enhanced when it was left IFG.

# Integrative Discussion

The main objective of the present study was to examine the involvement of the posterior LIFG region in the processing of different types of homographs, focusing on selection between competing representations within a biased context. Involvement was tested using excitatory tDCS electrical stimulation.

Studies have proposed different models for the way ambiguous written words are processed. The findings of the present study may strengthen the hybrid approach (Giora, 2003; Peleg et al., 2001) and challenge the selective attitude (Martin et al., 1999; Vu et al., 2000). According to the hybrid approach, when there is a context aimed at the subordinal meaning, it will strengthen the degree of excitation of this meaning, but will not inhibit the arousal of the dominant meaning. Here in the study, it was found that the phonological representation of the dominant meaning (/tIər/) arose entirely automatically, even when the reader wanted to reject it instantly. This excitation made it difficult to perform the reject operation. On the other hand, the current finding challenges the selective approach, according to which when there is a strong context it can guide the processing so that only the relevant meaning will arise. Here there was a suitable context, and the reader tried to overcome the dominant arousal, and yet it took longer compared to the corresponding condition.

Another major issue examined here was the question of the involvement of left IFG in the selection processes between representations of a homograph, when selecting subordinate meaning while suppressing irrelevant dominant meaning. Few studies have examined competition between representations using stimulating electrical stimulation, and what has been done has only referred to homophonic (semantic ambiguity) homograph (Ihara et al., 2014). There is another study relating to semantic versus phonological ambiguity, and it was done with TMS stimulation (Devlin et al., 2003). However, in these studies no emphasis on selection process was made. That is, they did not create a situation that guaranteed activation of the two competing representations and selection in one of them (while rejecting the other). In contrast, here the task began in context that led to the subordinal meaning, and at the same time the dominant meaning that should be rejected arose, thus ensuring a process of selection. The present study examined this selection process in both semantic and phonological ambiguity, combining excitatory stimulation in posterior LIFG. The findings showed that the stimulation improved performance when isolating the phonological ambiguity component (comparison between heterophonic and homophonic homographs), but not when isolating the semantic ambiguity (homophonic homograph versus unequivocal word). We will address the findings according to the different approaches to the role of IFG.

There are several approaches that relate to the role of IFG, and the most prominent are the specifics versus the general ones. Proponents of the general approach include Thompson-Schill et al., (2005) who argue that IFG is part of a left frontal region where regulatory processes and working memory are focused, and all cognitive and verbal skills attributed to the anterior region can be explained through regulatory and working memory features. Another general approach is that of Rodd et al., (2010) that IFG is a general area of choosing because it has been documented to be involved in selection processes in the semantic, phonological, and syntactic realms. Another approach is that targeted areas that specialize in specific functions can be identified within IFG. According to Bitan et al., (2017) the posterior region, corresponding to Broadman 44, is involved in phonological selection, while the anterior region, corresponding to Broadman 47 (and its homologous equivalent), is involved in semantic selection. According to Clos et al., (2013) IFG has five areas of specialization, and the most posterior regions among them are related to phonological functions (such as rhythmic sequences and vocal speaking). In the present study, excitatory stimulation (anodal) was performed on the posterior LIFG region, at the point of intersection between T3-FZ and F7-CZ. This point overlaps with the Broadman region 44-45 (de Aguiar et al., 2015; Cattaneo et al., 2011). The findings suggested that electrical stimulation improved the speed of response in the phonological ambiguity experiment. When participants had to reject the phonological representation of the dominant meaning (*tear* - /tIər/) and choose the subordinate meaning (/tεər/), the active stimulation group performed this more rapidly relative to those given sham. In contrast, the rejection of the dominant meaning when it came to semantic ambiguity did not improve following stimulation. This finding is consistent with the approach of Bitan et al., (2017) according to which posterior LIFG is involved in phonological rather than semantic selection. Also the more specific approach of Clos et al. (2013) fits the current findings, because according to it the most posterior parts are phonological, while the anterior ones are working memory and language and syntax functions.

The improvement in response can be attributed to two cognitive processes: strengthening the ability to choose the relevant meaning on the one hand, or improving the ability to suppress that meaning on the other hand. However, if active stimulation had an effect on the suppression ability of irrelevant meaning, then in all types of ambiguity tested there should have been improvement. Because this did not happen - it can be concluded that the stimulation did not affect the managerial ability or general cognitive control of suppressing irrelevant meanings.

# References

Ashby, J. (2016). Why Does Prosody Accompany Fluency? Re-conceptualizing the Role of Phonology in Reading. In Reading Fluency (pp. 65-89). Springer International Publishing.‏

Aziz-Zadeh, L., Cattaneo, L., Rochat, M., & Rizzolatti, G. (2005). Covert speech arrest induced by rTMS over both motor and nonmotor left hemisphere frontal sites. Journal of cognitive neuroscience, 17(6), 928-938.‏

Baciu, M. V., Rubin, C., Décorps, M. A., & Segebarth, C. M. (1999). fMRI assessment of hemispheric language dominance using a simple inner speech paradigm. NMR in Biomedicine, 12(5), 293-298.‏

Beeman, M., Friedman, R., Grafman, J., Perez, E., Diamond, S., & Lindsay, M. (1994). Summation priming and coarse semantic coding in the right hemisphere. *Cognitive Neuroscience, Journal of*, *6*(1), 26-45.‏

Berglund-Barraza, A., Tian, F., Basak, C., Hart, J., & Evans, J. L. (2020). Tracking Changes in Frontal Lobe Hemodynamic Response in Individual Adults With Developmental Language Disorder Following HD tDCS Enhanced Phonological Working Memory Training: An fNIRS Feasibility Study. *Frontiers in Human Neuroscience*, *14*, 362.‏

Binder, K. S., & Rayner, K. (1998). Contextual strength does not modulate the subordinate bias effect: Evidence from eye fixations and self-paced reading.*Psychonomic Bulletin & Review*, *5*(2), 271-276.‏

Bitan, T., Kaftory, A., Meiri-Leib, A., Eviatar, Z., & Peleg, O. (2017). Phonological ambiguity modulates resolution of semantic ambiguity during reading: An fMRI study of Hebrew. *Neuropsychology*, *31*(7), 759.‏

Bitan, T., Manor, D., Morocz, I. A., & Karni, A. (2005). Effects of alphabeticality, practice and type of instruction on reading an artificial script: An fMRI study. *Cognitive Brain Research*, *25*(1), 90-106.‏

Braun, M., Hutzler, F., Münte, T. F., Rotte, M., Dambacher, M., Richlan, F., & Jacobs, A. M. (2015). The neural bases of the pseudohomophone effect: phonological constraints on lexico-semantic access in reading. *Neuroscience*, *295*, 151-163.‏

Burgess, C., & Simpson, G. B. (1988). Cerebral hemispheric mechanisms in the retrieval of ambiguous word meanings. *Brain and Language*, *33*(1), 86-103.‏

Cattaneo, Z., Pisoni, A., & Papagno, C. (2011). Transcranial direct current stimulation over Broca's region improves phonemic and semantic fluency in healthy individuals. *Neuroscience*, *183*, 64-70.‏

Chiarello, C., Burgess, C., Richards, L., & Pollock, A. (1990). Semantic and associative priming in the cerebral hemispheres: Some words do, some words don't… sometimes, some places. *Brain and language*, *38*(1), 75-104.‏

Clos, M., Amunts, K., Laird, A. R., Fox, P. T., & Eickhoff, S. B. (2013). Tackling the multifunctional nature of Broca's region meta-analytically: co-activation-based parcellation of area 44. *Neuroimage*, *83*, 174-188.‏

Colbert-Getz, J., & Cook, A. E. (2013). Revisiting effects of contextual strength on the subordinate bias effect: Evidence from eye movements. *Memory & cognition*, *41*(8), 1172-1184.‏

de Aguiar, V., Bastiaanse, R., Capasso, R., Gandolfi, M., Smania, N., Rossi, G., & Miceli, G. (2015). Can tDCS enhance item-specific effects and generalization after linguistically motivated aphasia therapy for verbs?. *Frontiers in behavioral neuroscience*, *9*.‏

De Vries, M. H., Barth, A. C., Maiworm, S., Knecht, S., Zwitserlood, P., & Flöel, A. (2010). Electrical stimulation of Broca's area enhances implicit learning of an artificial grammar. *Journal of cognitive neuroscience*, *22*(11), 2427-2436.‏

Devlin, J. T., Matthews, P. M., & Rushworth, M. F. (2003). Semantic processing in the left inferior prefrontal cortex: a combined functional magnetic resonance imaging and transcranial magnetic stimulation study. *Journal of cognitive neuroscience*, *15*(1), 71-84.‏

Duffy, S. A., Morris, R. K., & Rayner, K. (1988). Lexical ambiguity and fixation times in reading. *Journal of Memory and Language, 27*, 429–446.

Fodor, J. A. (1983). The modularity of mind. Cambridge, MA: MIT Press.

Fregni, F., & Pascual-Leone, A. (2007). Technology insight: noninvasive brain stimulation in neurology—perspectives on the therapeutic potential of rTMS and tDCS. *Nature clinical practice Neurology*, *3*(7), 383-393.‏

Gernsbacher, M. A., & Faust, M. E. (1991). The mechanism of suppression: A component of general comprehension skill. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *17*(2), 245-262.‏

Gernsbacher, M. A., & St John, M. F. (2001). Modeling suppression in lexical access. *On the consequences of meaning selection: Perspectives on resolving lexical ambiguity*, 47-65.‏

Gibbs, R. W., & Gibbs Jr, R. W. (1994). *The poetics of mind: Figurative thought, language, and understanding*. Cambridge University Press.‏ Martin, C., Vu, H., Kellas, G., & Metcalf, K. (1999). Strength of discourse context as a determinant ofthe subordinate bias effect. *The Quarterly Journal of Experimental Psychology, 52A,* 813–839.

Giora, R. (1997). Understanding figurative and literal language: The graded salience hypothesis. *Cognitive Linguistics (includes Cognitive Linguistic Bibliography)*, *8*(3), 183-206.‏

Giora, R. (2003). *On our mind: Salience, context, and figurative language*. New York: Oxford University Press.‏

Gough, P. M., Nobre, A. C., & Devlin, J. T. (2005). Dissociating linguistic processes in the left inferior frontal cortex with transcranial magnetic stimulation. *The Journal of Neuroscience*, *25*(35), 8010-8016.‏

Grainger, J., Van Kang, M. N., & Segui, J. (2001). Cross-modal repetition priming of heterographic homophones. Memory & Cognition, 29(1), 53-61.‏

Hamilton, R. H., Chrysikou, E. G., & Coslett, B. (2011). Mechanisms of aphasia recovery after stroke and the role of noninvasive brain stimulation. *Brain and language*, *118*(1), 40-50.‏

Ihara, A. S., Mimura, T., Soshi, T., Yorifuji, S., Hirata, M., Goto, T., ... & Fujimaki, N. (2014). Facilitated lexical ambiguity processing by transcranial direct current stimulation over the left inferior frontal cortex. *Journal of cognitive neuroscience*.‏

Ihara, A., Hayakawa, T., Wei, Q., Munetsuna, S., & Fujimaki, N. (2007). Lexical access and selection of contextually appropriate meaning for ambiguous words. *NeuroImage*, *38*(3), 576-588.‏

Iyer, M. B., Mattu, U., Grafman, J., Lomarev, M., Sato, S., & Wassermann, E. M. (2005). Safety and cognitive effect of frontal DC brain polarization in healthy individuals. *Neurology*, *64*(5), 872-875.‏

Kavé, G. (2005). Phonemic fluency, semantic fluency, and difference scores: Normative data for adult Hebrew speakers. *Journal of Clinical and Experimental Neuropsychology*, *27*(6), 690-699.‏

Lavidor, M., & Ellis, A. (2003). Orthographic and phonological priming in the two cerebral hemispheres. *Laterality: Asymmetries of Body, Brain and Cognition*, *8*(3), 201-223.‏

Martin, C., Vu, H., Kellas, G., & Metcalf, K. (1999). Strength of discourse context as a determinant ofthe subordinate bias effect. *The Quarterly Journal of Experimental Psychology, 52A,* 813–839.

Matsuo, K., Chen, S. H. A., Hue, C. W., Wu, C. Y., Bagarinao, E., Tseng, W. Y. I., & Nakai, T. (2010). Neural substrates of phonological selection for Japanese character Kanji based on fMRI investigations. *Neuroimage*, *50*(3), 1280-1291.‏

Monti, A., Cogiamanian, F., Marceglia, S., Ferrucci, R., Mameli, F., Mrakic-Sposta, S., ... & Priori, A. (2008). Improved naming after transcranial direct current stimulation in aphasia. *Journal of Neurology, Neurosurgery & Psychiatry*, *79*(4), 451-453.

Moss, H. E., Abdallah, S., Fletcher, P., Bright, P., Pilgrim, L., Acres, K., & Tyler, L. K. (2005). Selecting among competing alternatives: selection and retrieval in the left inferior frontal gyrus. *Cerebral Cortex*, *15*(11), 1723-1735.‏

Nitsche, M. A., Cohen, L. G., Wassermann, E. M., Priori, A., Lang, N., Antal, A., ... & Pascual-Leone, A. (2008). Transcranial direct current stimulation: state of the art 2008. *Brain stimulation*, *1*(3), 206-223.‏

Nixon, P., Lazarova, J., Hodinott-Hill, I., Gough, P., & Passingham, R. (2004). The inferior frontal gyrus and phonological processing: an investigation using rTMS. *Journal of cognitive neuroscience*, *16*(2), 289-300.‏

Onifer, W., & Swinney, D. A. (1981). Accessing lexical ambiguities during sentence comprehension: Effects of frequency of meaning and contextual bias. *Memory and Cognition, 9*(3), 225–236.

Opitz, B., Müller, K., & Friederici, A. D. (2003). Phonological processing during language production: fMRI evidence for a shared production-comprehension network. *Cognitive Brain Research*, *16*(2), 285-296.‏

Osovlanski, H., & Mashal, N. (2017). The effects of transcranial direct current stimulation on pragmatic processing. *Journal of Neurolinguistics*, *44*, 239-248.‏

Peleg, O., & Eviatar, Z. (2008). Hemispheric sensitivities to lexical and contextual constraints: Evidence from ambiguity resolution. *Brain and Language, 105*, 71–82.

Peleg, O., & Eviatar, Z. (2009). Semantic asymmetries are modulated by phonological asymmetries: Evidence from the disambiguation of homophonic versus heterophonic homographs. *Brain and cognition*, *70*(1), 154-162.‏

Peleg, O., & Eviatar, Z. (2012). Understanding Written Words: Phonological, Lexical, and Contextual Effects in the Cerebral Hemispheres. *The Handbook of the Neuropsychology of Language Volume 1 Language Processing in the Brain: Basic Science*, 59.‏

Peleg, O., Giora, R., & Fein, O. (2008). Resisting contextual information: You can't put a salient meaning down. *Lodz Papers in Pragmatics*, *4*(1), 13-44.‏

Peleg, O., Giora, R., Fein, O. (2001). Salience and context effects: two are better than one. *Metaphor and Symbol, 16*, 173–192

Peleg, O., Manevitz, L., Hazan, H., & Eviatar, Z. (2010). Two hemispheres—two networks: a computational model explaining hemispheric asymmetries while reading ambiguous words. *Annals of Mathematics and Artificial Intelligence*, *59*(1), 125-147.‏

Perrone-Bertolotti, M., Kujala, J., Vidal, J. R., Hamame, C. M., Ossandon, T., Bertrand, O., ... & Lachaux, J. P. (2012). How silent is silent reading? Intracerebral evidence for top-down activation of temporal voice areas during reading. Journal of Neuroscience, 32(49), 17554-17562.‏

Pisoni, A., Cerciello, M., Cattaneo, Z., & Papagno, C. (2017). Phonological facilitation in picture naming: When and where? A tDCS study. Neuroscience, 352, 106-121.‏

Pisoni, A., Papagno, C., & Cattaneo, Z. (2012). Neural correlates of the semantic interference effect: New evidence from transcranial direct current stimulation. Neuroscience, 223, 56-67.‏

Priori, A. (2003). Brain polarization in humans: a reappraisal of an old tool for prolonged non-invasive modulation of brain excitability. *Clinical Neurophysiology*, *114*(4), 589-595.‏

Rayner, K., & Duffy, S. A. (1986). Lexical complexity and fixation times in reading: Effects of word frequency, verb complexity, and lexical ambiguity.*Memory & Cognition*, *14*(3), 191-201.

Rayner, K., Pacht, J. M., & Duffy, S. A. (1994). Effects of prior encounter and global discourse bias on the processing of lexically ambiguous words: Evidence from eye fixations. *Journal of Memory and Language*, *33*(4), 527-544.‏

Rodd, J. M., Davis, M. H., & Johnsrude, I. S. (2005). The neural mechanisms of speech comprehension: fMRI studies of semantic ambiguity. *Cerebral Cortex*, *15*(8), 1261-1269.‏

Rodd, J. M., Longe, O. A., Randall, B., & Tyler, L. K. (2010). The functional organisation of the fronto-temporal language system: evidence from syntactic and semantic ambiguity. *Neuropsychologia*, *48*(5), 1324-1335.‏

Sakai, K. L., Noguchi, Y., Takeuchi, T., & Watanabe, E. (2002). Selective priming of syntactic processing by event-related transcranial magnetic stimulation of Broca's area. *Neuron*, *35*(6), 1177-1182.‏

Savill, N., Ashton, J., Gugliuzza, J., Poole, C., Sim, Z., Ellis, A. W., & Jefferies, E. (2015). tDCS to temporoparietal cortex during familiarisation enhances the subsequent phonological coherence of nonwords in immediate serial recall. *Cortex*, *63*, 132-144.‏

Sehm, B., Schnitzler, T., Obleser, J., Groba, A., Ragert, P., Villringer, A., & Obrig, H. (2013). Facilitation of inferior frontal cortex by transcranial direct current stimulation induces perceptual learning of severely degraded speech. *Journal of Neuroscience*, *33*(40), 15868-15878.‏

Simpson, G. B. (1984). Lexical ambiguity and its role in models of word recognition. *Psychological Bulletin, 96*, 316–340.

Smolka, E., & Eviatar, Z. (2006). Phonological and orthographic visual word recognition in the two cerebral hemispheres: Evidence from Hebrew. *Cognitive Neuropsychology*, *23*(6), 972-989.

Swinney, D. (1979). Lexical access during sentence comprehension: Reconsideration of context effects. *Journal of Verbal Learning and Verbal Behavior, 18*, 645–660.

Thompson-Schill, S. L., Bedny, M., & Goldberg, R. F. (2005). The frontal lobes and the regulation of mental activity. *Current opinion in neurobiology*, *15*(2), 219-224.‏

Utz, K. S., Dimova, V., Oppenländer, K., & Kerkhoff, G. (2010). 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*, *48*(10), 2789-2810.‏

Van Petten, C. (2002). Lexical ambiguity resolution. In L. Nadel (Ed.), *Encyclopedia of Cognitive Science* (pp 867-872). London: Macmillan.

Van Petten, C., & Kutas, M. (1990). Interactions between sentence context and word frequencyinevent-related brainpotentials. *Memory & Cognition*, *18*(4), 380-393.‏

Van Petten, C., & Kutas, M. (1991). Influences of semantic and syntactic context on open-and closed-class words. *Memory & Cognition*, *19*(1), 95-112.‏

Vigneau, M., Beaucousin, V., Herve, P. Y., Duffau, H., Crivello, F., Houde, O., ... & Tzourio-Mazoyer, N. (2006). Meta-analyzing left hemisphere language areas: phonology, semantics, and sentence processing. *Neuroimage*, *30*(4), 1414-1432.‏

Vu, H., Kellas, G., Metcalf, K.,&Herman, R. (2000). The influence of global discourse on lexical ambiguityresolution. *Memory & Cognition, 28,* 236–252.

Wechsler, D. (2008). Wechsler adult intelligence scale–Fourth Edition (WAIS–IV). *San Antonio, TX: NCS Pearson*.‏

Wheat, K. L., Cornelissen, P. L., Frost, S. J., & Hansen, P. C. (2010). During visual word recognition, phonology is accessed within 100 ms and may be mediated by a speech production code: evidence from magnetoencephalography. *The Journal of neuroscience*, *30*(15), 5229-5233.‏

Yankovitz, B. E., & Mashal, N. (2020). Can brain stimulation improve semantic joke comprehension?. *Journal of Cognitive Psychology*, *32*(4), 357-368.‏

Zaidel, E., & Peters, A. M. (1981). Phonological encoding and ideographic reading by the disconnected right hemisphere: Two case studies. *Brain and Language*, *14*(2), 205-234.‏

Zempleni, M. Z., Renken, R., Hoeks, J. C., Hoogduin, J. M., & Stowe, L. A. (2007). Semantic ambiguity processing in sentence context: Evidence from event-related fMRI. *Neuroimage*, *34*(3), 1270-1279.‏