

Modulating Brain Mechanisms Resolving Lexico-semantic Interference during Word Production: A Transcranial Direct Current Stimulation Study

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Abstract

■ The aim of the current study was to shed further light on control processes that shape semantic access and selection during speech production. These processes have been linked to differential cortical activation in the left inferior frontal gyrus (IFG) and the left middle temporal gyrus (MTG); however, the particular function of these regions is not yet completely elucidated. We applied transcranial direct current stimulation to the left IFG and the left MTG (or sham stimulation) while participants named pictures in the presence of associatively related, categorically related, or unrelated distractor words. This direct modulation of target regions can help to better delineate the functional role of these regions in lexico-semantic selection. Independent of stimulation, the data show interference (i.e., longer naming latencies) with categorically related distractors and facilitation (i.e., shorter naming latencies) with associatively related distractors. Importantly,

stimulation location interacted with the associative effect. Whereas the semantic interference effect did not differ between IFG, MTG, and sham stimulations, the associative facilitation effect was diminished under MTG stimulation. Analyses of latency distributions suggest this pattern to result from a response reversal. Associative facilitation occurred for faster responses, whereas associative interference resulted in slower responses under MTG stimulation. This reduction of the associative facilitation effect under transcranial direct current stimulation may be caused by an unspecific overactivation in the lexicon or by promoting competition among associatively related representations. Taken together, the results suggest that the MTG is especially involved in the processes underlying associative facilitation and that semantic interference and associative facilitation are linked to differential activation in the brain. ■

INTRODUCTION

Producing language is, in short, saying the right word at the right time. The involved processes, however, are complex and not yet fully understood. There is consensus that a key aspect in word production is choosing the appropriate “entry” from the mental lexicon at a particular point in time. Yet, it is still not fully understood how this works exactly and, especially, how selecting the right candidate word succeeds in the presence of competing alternatives. If lexico-semantic selection works properly, then the right word is produced, but if it fails, certain types of errors can occur (e.g., substitution errors; Garrett, 1992). It has been suggested that these errors are because of disturbances in “regulatory control processes” of the semantic system (see Corbett, Jefferies, & Ralph, 2011; Jefferies & Lambon Ralph, 2006), but what exactly happens during these control processes is a topic of heated discussion (Roelofs, 2008; Mahon, Costa, Peterson, Vargas, & Caramazza, 2007). It is further not clear which brain structures are involved in these processes. One way to

address these research questions is to experimentally create situations of high and low selection demands, for example, by presenting different types of distractor words in the context of a picture naming task (see below), and to modulate the activity of target brain regions in these situations with transcranial stimulation techniques. The effects of this modulation on performance in low/high selection conditions can help to better understand how the selection of appropriate word candidates works in the human brain.

From semantic priming studies, we know that activation of a target semantic concept also activates entries that are semantically related to the target. These observations are consistent with the spreading activation theory of lexical access, which assumes that activation automatically spreads among related nodes in the lexico-semantic network (e.g., Collins & Loftus, 1975; Posner & Snyder, 1975). However, if this is the case, how can the target entry finally be selected among these coactivated representations? “Activation” or “threshold models” propose that the activation of a lexico-semantic node leads to an activation of all corresponding nodes and that the first node reaching threshold fires, allowing it to dominate subsequent processing (see, e.g., Rapp & Goldrick, 2000;

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Caramazza & Hillis, 1990; Dell, 1986; see also Mahon et al., 2007; Finkbeiner & Caramazza, 2006; Costa, Alario, & Caramazza, 2005). Other models more strongly emphasize the idea of competition between candidate entries. According to these “competition models,” the coactivation via spreading activation creates a situation of high competition between candidates, which has to be resolved (see, e.g., Levelt, Roelofs, & Meyer, 1999; Caramazza, 1997; Roelofs, 1992, 1997; Schriefers, Meyer, & Levelt, 1990), either by a critical difference threshold or by lateral inhibition (see Goldrick, 2007; Levelt, 1999; Roelofs, 1992, 1997; Houghton & Tipper, 1996; Harley, Jones, Dunbar, & Macandrew, 1995; Wheeldon & Monsell, 1994; Berg & Schade, 1992; Schriefers et al., 1990). In addition to these lexicon-based mechanisms, other authors suggest mechanisms that are extrinsic to the mental lexicon. On the basis of theories of attentional selection, they assume a selection mechanism that operates in a controlled top-down fashion to ensure correct selection by influencing the competitive weights of lexical candidates (Kan & Thompson-Schill, 2004; Wilshire & McCarthy, 2002; Desimone & Duncan, 1995).

Although there is ongoing debate on these theoretical models of semantic selection, empirical evidence from speech error analyses and experimental studies are often interpreted as an index of competition between lexico-semantic candidate entries during speech production. Specifically, the effects seen in the picture-word interference (PWI) paradigm are considered as important empirical markers of the selection by competition process (see, e.g., Hantsch, Jescheniak, & Schriefers, 2005, 2009; Levelt, 1999; but see also Mahon et al., 2007; Costa et al., 2005). The PWI paradigm allows modulating the selection demands bidirectionally by creating either a situation of high or low selection demands. In the high selection condition, the participant’s task is to name a picture while the activation of a competitor is boosted by the (near) simultaneous presentation of a semantically related word. It is well documented that these distractors slow down the naming latency of the picture, which has been termed the semantic interference (SI) effect. This effect is assumed to be an index of the coactivation of competing lexical information (see, e.g., Levelt et al., 1999). In contrast, semantic selection can also be facilitated by presenting priming semantic information, for example, by showing an associatively related word before the target picture. This leads to significant faster naming latencies, that is, an associative facilitation effect (e.g., Alario, Segui, & Ferrand, 2000).

Notably, only particular distractors induce interference or facilitation effects in the PWI paradigm. For distractors that come from the same semantic category as the target (categorical distractors, e.g., truck-car), it is well documented that they lead to strong interference in the PWI paradigm, both in visual (e.g., Sailor, Brooks, Bruening, Seiger-Gardner, & Guterman, 2009; Mahon et al., 2007; Alario et al., 2000; Glaser & Dungelhoff, 1984) as well

as in auditory presentation of a distractor (e.g., Damian & Martin, 1999; Schriefers et al., 1990). It has further been shown that categorical interference effects and associative facilitation effects in PWI experiments follow different time courses. Interference effects induced by categorical distractors can be obtained most reliably with short negative SOA between -150 and 0 msec and tend to disappear at positive SOAs (see, e.g., Sailor et al., 2009; Mahon et al., 2007; Damian & Martin, 1999; Starreveld & LaHeij, 1996; Schriefers et al., 1990; Glaser & Dungelhoff, 1984). In contrast, for associatively related distractors, the facilitation effects are greatest at negative SOAs (from -450 to 0 msec) and tend to be more pronounced at longer negative SOAs (Sailor et al., 2009; Alario et al., 2000). At a theoretical level, SI is mostly attributed to lexical competition on the lemma level (e.g., Roelofs, 1992) or postlexical selection processes (e.g., Mahon et al., 2007), whereas associative facilitation has been attributed to conceptual or lexical priming (e.g., Abdel Rahman & Melinger, 2009).

Yet, it is still an unresolved question which neurobiological mechanisms are the underpinnings of these effects in the brain. In a number of fMRI studies, Thompson-Schill and colleagues manipulated semantic selection demands and reported higher activity in the left frontal cortex as well as in the left temporal and medial frontal areas during tasks imposing high selection demands (Nagel, Schumacher, Goebel, & D’Esposito, 2008; Snyder, Feigenson, & Thompson-Schill, 2007; Thompson-Schill, D’Esposito, & Kan, 1999; Thompson-Schill, D’Esposito, & Aguirre, 1997). Especially, activation in the left inferior frontal gyrus (IFG) is typically seen to increase during the selection of semantic features (Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005), the suppression of interfering semantic or phonological information (Righi, Blumstein, Mertus, & Worden, 2010; de Zubicaray, McMahon, Eastburn, Pringle, & Stephensen, 2006; Moss et al., 2005), blocked cycled naming (Heim, Eickhoff, Friederici, & Amunts, 2009; Schnur et al., 2009), and ambiguity resolution (Whitney, Grossman, & Kircher, 2009; Bedny, McGill, & Thompson-Schill, 2008). Considering these results, it has been suggested that the role of the left IFG is to bias selection toward task-relevant lexico-semantic information and to exert inhibitory control over task-irrelevant information (Lau, Phillips, & Poeppel, 2008; Badre et al., 2005). Next to the IFG, activation in the left posterior middle temporal gyrus (pMTG) is frequently observed during tasks involving lexico-semantic selection (Snyder et al., 2007; Thompson-Schill et al., 1997). However, in contrast to the IFG, the role of this region is more controversial. It has been suggested that its function may rather be related to the retrieval of information from the mental lexicon than the selection process itself (Badre et al., 2005; Wagner, Pare-Blagoev, Clark, & Poldrack, 2001). Results, which indicate that the pMTG is sensitive to facilitatory priming effects, support this assumption (Kuperberg, Lakshmanan, Greve, & West,

2008; Gold et al., 2006). Furthermore, left pMTG activation increases during blocked naming especially in those situations when many words of the same semantic cohort have to be retrieved (Heim et al., 2009; Schnur et al., 2009). This may link its function to the activation of semantic cohort members and related inhibition processes.

To find out more about these processes, the PWI paradigm has been investigated with fMRI. Yet, the conducted experiments led to heterogeneous results. Spalek and Thompson-Schill (2008), for instance, found evidence for the involvement of left ventral temporal areas as well as the left frontal and left parietal cortex in semantic selection during speech production. The reported activations, however, were weak (only seen in ROI analyses), and the behavioral effects were missing, making the results difficult to interpret. Two additional fMRI studies used the PWI paradigm and reported an involvement of the left frontal, temporal, and occipital brain areas in semantic selection (de Zubicaray & McMahon, 2009; de Zubicaray, McMahon, Wilson, & Muthiah, 2001). The results of these studies, however, are again difficult to integrate because the first study used a nonlanguage control condition to contrast the language task against and the latter study reported mainly deactivations. The most elaborate study on this topic was conducted by Abel and colleagues (Abel et al., 2009). In their experiment, the PWI paradigm was applied with different types of distractor words (categorical, associative, phonological, and unrelated). Their results suggest that the effects of associative and categorical distractors are at least partly dissociable in the brain, with the former located in the left MTG and the latter located in the left IFG. Again, however, these effects were only seen in ROI analyses. In summary, there is neuroimaging evidence suggesting that the left IFG and the left pMTG may play a critical role in semantic selection, but this evidence is heterogeneous, partly problematic from an experimental point of view and thus controversial.

To further integrate and validate current research findings, we conducted a meta-analysis (activation likelihood estimation [ALE]) on fMRI studies involving lexico-semantic retrieval and selection. The results of this analysis showed noticeable clusters in the left IFG and in the left pMTG (Figure 1) as well as in the cingulate cortex, the right MFG, and the left angular gyrus. Taken together, the neuroimaging literature provides evidence that the left IFG and the left pMTG are functionally relevant for processes of lexico-semantic selection.

Evidence for this comes also from transcranial direct current stimulation (tDCS) and TMS studies. On the basis of the results obtained by Wagner et al. (2001) and Thompson-Schill et al. (1997), Whitney, Kirk, O'Sullivan, Ralph, and Jefferies (2011, 2012) recently showed in TMS studies that the left IFG and the left posterior MTG support controlled retrieval and selection of semantic knowledge in a language-specific way. Wirth et al. (2011) showed in a tDCS study that application of anodal tDCS (a-tDCS)

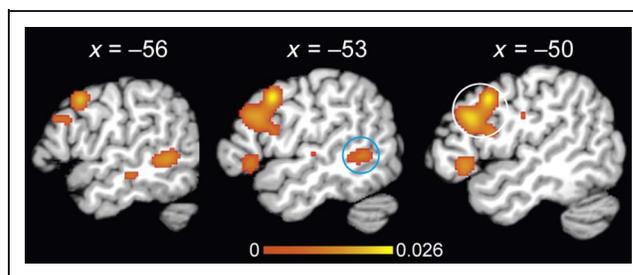


Figure 1. ALE meta-analysis. Neural correlates of lexico-semantic selection processes as revealed by the ALE meta-analysis. The two regions with the highest ALE values in the left frontal (white circle) and the left temporal cortex (blue circle) were chosen as seed regions for tDCS stimulation (for details, see text). The color bar depicts the ALE values. x is the MNI coordinate.

over the left frontal cortex reduces the effect of growing naming latencies during blocked naming, that is, that it improves selection in a situation of high competition. They suggested that these results reflect the elevation of prefrontal inhibitory functions by anodal tDCS over the left pFC. Thus, there is some evidence that facilitatory stimulation with anodal tDCS might support inhibitory control mechanisms resolving SI during speech production. However, so far, no study has directly examined the effects of tDCS stimulation on semantic selection during performance of the PWI paradigm.

This was done in the current study. Specifically, we applied in an on-line stimulation protocol anodal tDCS on a frontal and a temporal target region in situations of high and low selection demands and tested the following hypotheses formulated by Abel and colleagues (2009): (1) The left IFG is more related to the SI effect induced by categorically related distractors, and (2) the left MTG is more sensitive to the facilitation effect induced by associatively related primes. Following these assumptions, the stimulation of the two target regions should lead to differential effects in the different conditions of the PWI paradigm. The results of these experiments may help to improve our understanding of the differential roles of these brain regions during lexico-semantic selection.

METHODS

Participants

Thirty-six healthy volunteers (mean age = 26.2 years, $SD = 2.98$ years) participated in the tDCS study. All participants were right-handed native speakers of German with normal or corrected-to-normal vision. They had no history of neurological or psychiatric illness, no drug or alcohol abuse, no family history of epilepsy, no current pregnancy (women did a pregnancy test before each session), no chronic medical disease, and no migraine (or other chronic headaches). Participants gave written informed consent before the experiment. The experiment was approved by the local ethics committee of

the University Leipzig, and participants were treated in accordance with the declaration of Helsinki.

Task and Stimuli

The PWI paradigm was applied in the tDCS experiment. The participant's task was to name a picture in the presence of a visual distractor word. There were four experimental distractor conditions: (1) categorically related, (2) associatively related, (3) unrelated control for categorically related distractors, and (4) unrelated control for associatively related distractors. To create Conditions 3 and 4, the distractors from Conditions 1 and 2 were reassigned to unrelated pictures. Hence, the unrelated control condition was composed of the same pictures and words as the corresponding related condition, and the results of direct comparisons between both conditions cannot be biased by differences in the stimulus sets. On the basis of behavioral pretests, we selected SOAs of -300 and -100 msec, which had yielded the largest associative facilitation and SI effects, for the tDCS study.¹

The set of experimental stimuli consisted of 120 black-and-white line drawings (40 for the categorical condition and its control, 40 for the associative condition and its control, 40 for filler items) of simple objects with a high naming agreement as verified in a pretest. The pictures were sized to fill a square of about 7×7 cm. The two sets of experimental pictures (associative, categorical) were matched with regard to parameters influencing picture naming speed, including lexical frequency and word length (see Table 1 for stimulus characteristics). The categorical distractors were within-level distractors, that is, they were drawn from the same level of abstraction (i.e., category) as the target words. The associatively related distractors were selected based on an association database (Melinger & Weber, 2006, www.coli.uni-saarland.de/projects/nag; Table 1). We controlled for an overlap between the two related conditions, that is, that the categorically related distractors did not have associative relationships to the targets and that the associative distractors were not taken from the same semantic category as the targets. Unrelated distractor–target pairs were neither semantically nor associatively related to distractors and targets. Also, phonological (onset-)overlap between target and distractor was avoided for all picture–word pairs. As already pointed out, each distractor word occurred once as a related distractor in the semantically related conditions and once as an unrelated distractor in the corresponding control condition, so that the stimuli sets in the related and its unrelated control condition were perfectly matched. Additionally, the distractors occurring in the two related conditions were matched for lemma frequency, number of syllables, and number of graphemes (see Table 1). To avoid differences in visual masking by distractors of different lengths for a given target, distractors were presented embedded in a rectangular field in background color sized to hold the longest distractor word assigned to a given target. Thus, the rectangle's size varied between pictures but was identical in the related and unrelated condition for each picture. Finally, we created an additional set of filler items (40 pictures with unrelated distractors) that were different from the stimuli used in the experiment.

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Trial Structure

The distractor word was presented either 300 or 100 msec before picture onset (SOAs of -300 and -100 msec). Then, the target picture was presented for 800 msec, followed by a fixation cross. The word remained on the screen during picture presentation. The response interval started at picture onset with a duration of 3000 msec. Total trial length was 4000 msec (Figure 2A).

Table 1. Characteristics of Stimuli

Feature	Pictures			Distractor Words		
	Associative	Categorical	<i>p</i>	Associative	Categorical	<i>p</i>
Associative strength to target	–	–	–	58.9 (\pm 23.8)	0.9 (\pm 1.2)	<.001
Lemma frequency	41.7 (\pm 80.3)	41.8 (\pm 76.5)	.997	22.7 (\pm 32.3)	34.2 (\pm 86.1)	.439
Number of syllables	1.7 (\pm 0.5)	1.7 (\pm 0.5)	.825	1.8 (\pm 0.5)	1.8 (\pm 0.5)	.666
Number of phonemes/graphemes	4.3 (\pm 0.9)	4.3 (\pm 1.0)	.910	5.4 (\pm 1.3)	5.2 (\pm 1.2)	.523
Name agreement	91.8 (\pm 10.7)	93.2 (\pm 7.9)	.507	–	–	–
Image agreement	4.1 (\pm 0.6)	4.1 (\pm 0.6)	.538	–	–	–
Visual complexity	2.6 (\pm 0.7)	2.6 (\pm 0.7)	.707	–	–	–
Familiarity	2.9 (\pm 1.0)	3.2 (\pm 2.2)	.257	–	–	–

All values are mean (\pm standard deviation). Frequency values reflect normalized lemma frequency counts taken from dlex lexical database (Heister et al., 2011; www.dlexdb.de). Name agreement scores, image agreement ratings, familiarity ratings, and visual complexity ratings were taken from German picture-naming norms (cf. Mädebach, Oppermann, Babeliowsky, & Jescheniak, 2013).

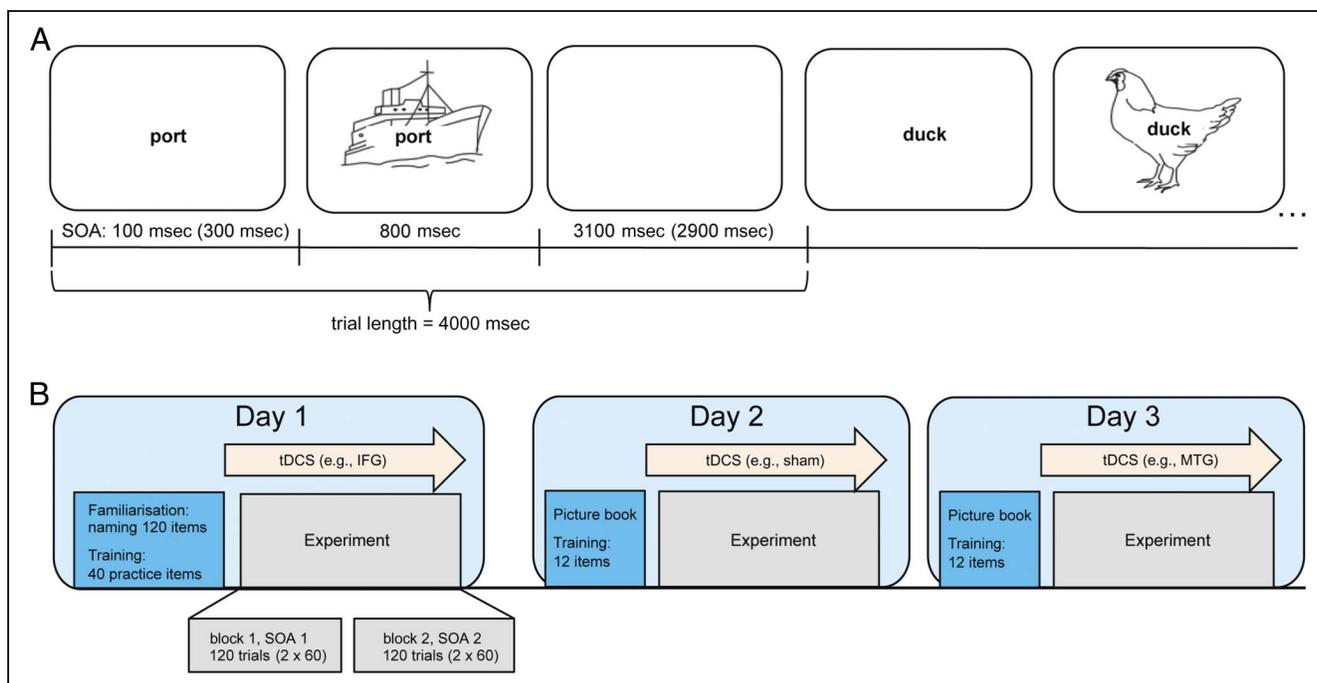


Figure 2. Trial structure and design. (A) Trial structure of the tDCS experiment. The distractor word was presented with an SOA of -100 (categorical condition) or -300 (associative condition) msec and remained on the screen during target presentation (the times in parentheses are the presentation times for the associative condition). The first example is a trial of the associatively related condition; the second, a trial of the categorically related condition (in the experiment presented in different blocks). (B) Design of the tDCS experiment (for details, see text).

Design and Procedure

For each participant, there were three experimental sessions. The sessions consisted of different parts: (1) instruction phase, (2) familiarization phase (both only in the first session), (3) training phase, and (4) main experiment (see Figure 2B). During the instruction phase, participants were introduced to the task and saw a booklet with the target pictures and their names. They were instructed to name the target pictures as fast and accurately as possible. During the familiarization phase in Session 1, pictures were presented without distractors and participants named each picture once. During the training phase, participants named the practice items (taken from the filler items) with distractors to get used to the PWI task (40 practice items in Session 1, 12 practice items in Sessions 2 and 3). After the training phase, the neuronavigation and the positioning of the tDCS-stimulation electrodes took place (for details, see below). Then, the stimulation started, and we waited for 5 min, during which participants relaxed (to reach a steady state). After this consolidation phase, the main experiment started and the tDCS stimulation continued over the next 20 min (on-line stimulation protocol).

During the main experiment, participants performed the PWI task. There were 40 trials per condition and four conditions (see above). The associatively related and categorically related conditions (with their corresponding control condition) were presented in different blocks with their specific SOA (SOA of -100 msec for categorical distractors and -300 msec for associative distractors).

Thus, the experiment was composed of two blocks. Per block, there were 40 related trials, 40 unrelated control trials, and 40 filler trials (20 filler items each presented twice with two different unrelated distractor words), thus having 120 trials per block. Related, unrelated, and filler trials were presented intermixed; the sequence of conditions for a given target item was counterbalanced across participant groups. Each item and each distractor within each block was shown once, before any item or distractor was repeated. After every 60 trials, there was a short break; after the break, the experiment always continued with three filler items. With a trial length of 4 sec and 120 trials per block, this leads to a total duration of about 8 min for one experimental block and ca. 20 min for two blocks (including pauses). Together with the instruction and training/practice phase, this sums up to a total duration of about 45–60 min, among them is 25 min of tDCS stimulation. Participants were invited for three sessions on separate days (for anodal IFG, anodal MTG, and sham stimulation). To avoid carryover effects, sessions were at least 1 week apart. The order of stimulation modalities was counterbalanced across participants and scanning days.

Apparatus

Stimuli were presented on a 17-in. monitor with a resolution of 1280×1024 pixels. Participants were seated with a viewing distance of about 60 cm to the screen. Stimulus presentation and data collection were controlled by the

NESU system (MPI for Psycholinguistics, Nijmegen, The Netherlands). Responses were registered with a microphone, and speech-onset latencies were measured using a Nesubox-Lite hardware voicekey.

Neuronavigation and tDCS

The two target regions were identified based on our meta-analysis of fMRI studies investigating lexico-semantic retrieval and selection. The meta-analysis included 14 fMRI studies on lexico-semantic selection (total data from 221 participants with 122 activation foci). All studies involved healthy participants and provided peak coordinates based on whole-brain statistical analyses (ROI analyses were excluded). Coordinates were converted to the Montreal Neurological Institute (MNI) space, and probabilistic maps were constructed using the ALE method (Eickhoff et al., 2009; Turkeltaub, Eden, Jones, & Zeffiro, 2002), implemented in the GingerALE software package (brainmap.org/ale/index.html), using threshold of $p < .05$ (corrected for multiple comparisons by false discovery rate) and a minimal cluster volume of 200 mm^3 . The highest frontal and temporal activation peaks revealed by this analysis (i.e., the regions with the highest ALE values) were taken as target regions for neuronavigation in the tDCS experiment (MNI coordinates $[x, y, z]$, IFG: $-50, 15, 29$; pMTG: $-56, -48, -2$). We used individual structural T1-weighted images of each participant to guide the neuronavigation (Brainsight Version 1.7.8, Montreal, Canada) and used individual cortical landmarks to check (and correct, if necessary) the localization. In addition, four anatomical landmarks on the head (nasion, tip of nose, right/left tragus) were used to coregister the MR image with the participant's head.

tDCS stimulation was delivered by a common DC generator (Eldith DC Stimulator, NeuroConn GmbH, Germany) in an on-line stimulation protocol. Anodal stimulation was delivered using a small active electrode ($5 \text{ cm} \times 5 \text{ cm} = 25 \text{ cm}^2$) and as reference electrode served a large (and thus inactive) cathode ($10 \text{ cm} \times 5 \text{ cm} = 50 \text{ cm}^2$). The anode was placed above one of the target regions (either above the left IFG or the left pMTG, depending on the session and the randomization protocol), and the reference electrode was placed over the contralateral supra-orbital region. Instead of sponges, EEG gel was used to assure good impedance (see Minhas et al., 2010). DC stimulation was delivered for 25 min at 2-mA intensity (including 30-sec ramp up and 30-sec ramp down). The first 5 min after ramp up were used to reach a stable state, and then, the experiment started. Stimulation continued through the entire task and ended shortly after finishing the experiment. For sham stimulation, the stimulator did only ramp up (30 sec) but did not induce any further current. For sham stimulation, the sham electrode was placed over the frontal target region in one half of the participants and over the temporal target region in the

other half of the group. After having performed all three sessions, participants were asked which session they thought had been the sham session. Right answers were at chance level, showing that sham tDCS and real tDCS could not be differentiated by participants. The impedance was controlled throughout each tDCS session and was $< 4 \Omega$ in all participants (mean = 2.75Ω , $SD = 0.59 \Omega$). Participants were further asked after each session whether they had noticed any adverse effects. They reported no such effects (only a few participants reported an itching sensation under the electrodes).

Analyses

Observations were coded as erroneous and discarded from the RT analyses whenever any of the following conditions held true: (a) no response or an unexpected response had been given; (b) a disfluency occurred or an utterance was corrected; (c) a nonspeech sound preceded the target utterance, triggering the voice key; and (d) the voice key was triggered within 300 msec, not triggered within 3000 msec or a technical error occurred (509 observations, 2.9%). Errors of types a–c were submitted to error analyses. Naming latencies deviating from a participant's and an item's mean by more than 2 SD were considered outliers and also discarded from the RT analyses (361 observations, 2.1%).

All analyses were conducted separately for the associative and categorical conditions. We do not report overall analysis including type of relation (associative vs. categorical) as a factor because (a) we explicitly wanted to distinguish between the effects of the tDCS stimulation on associative facilitation and on categorical interference effects and (b) the factor "type of relation" was confounded with SOA and with the use different item sets. Therefore, possible effects of this factor would not allow for a clear-cut interpretation. For both types of relations, the following analyses are reported. First, to establish the stability of the semantic and associative distractor effects across the three sessions, averaged RTs and error rates were submitted to ANOVAs involving the fixed factors Session (1–3) and Relatedness (related vs. unrelated). Second, RTs and error rates were submitted to ANOVAs involving the fixed factors stimulation type (left IFG, left MTG, sham) and relatedness (related vs. unrelated) to examine the main effects of stimulation and potential interactions between the distractor effects and the stimulation. Furthermore, analyses of latency distributions of semantic and associate distractor effects under the different stimulations are reported. Latency distributions were analyzed in two ways. Vincentized cumulative distribution curves (Roelofs, 2008; Ratcliff, 1979) were obtained by splitting the rank-ordered latencies (per participant or item) into quintiles (separated by type of relation, stimulation, and relatedness) before averaging across these quintile means (e.g., Piai, Roelofs, & Schriefers, 2011,

Table 2. Results for Associatively Related Distractors

	<i>RT</i>	%	μ	σ	τ
<i>IFG Stimulation</i>					
Associatively related	692 (11)	2.4 (0.5)	587 (11)	45 (5)	105 (5)
Unrelated	719 (12)	3.3 (0.6)	622 (11)	49 (7)	98 (8)
Difference	-27*** (7)	-0.9 (0.6)	-35*** (6)	-4 (5)	7 (9)
<i>MTG Stimulation</i>					
Associatively related	695 (12)	2.6 (0.4)	589 (12)	43 (7)	107 (11)
Unrelated	704 (8)	2.2 (0.5)	622 (9)	53 (6)	82 (7)
Difference	-9 (7)	0.4 (0.5)	-33** (9)	-10 (8)	25* (12)
<i>No Stimulation (Sham)</i>					
Associatively related	683 (11)	2.2 (0.5)	597 (13)	52 (6)	86 (8)
Unrelated	706 (11)	2.4 (0.5)	612 (9)	48 (5)	97 (8)
Difference	-23*** (5)	-0.2 (0.5)	-15 (9)	4 (8)	-11 (10)

Mean naming latencies (in msec), error rates (in percent), and ex-Gaussian parameters (μ , σ , τ) for the associatively related and unrelated conditions, separated by stimulation location and relatedness.

Standard errors of the mean are given in parentheses.

* $p < .05$.

** $p < .01$.

*** $p < .001$.

2012), and corresponding ANOVAs involving the factors Quintile and Relatedness are reported for each stimulation and type of relation. Ex-Gaussian parameters of the latency distributions were obtained with QMPE (Heathcote, Brown, & Cousineau, 2004) using quantile maximum likelihood estimation with quintiles (e.g., Brown & Heathcote, 2003) and submitted to ANOVAs with the fixed factors Stimulation Type and Relatedness. In all cases, in which the sphericity assumption was violated (Mauchly test, $p < .05$), Greenhouse–Geisser corrected degrees of freedom and p values are reported.

RESULTS

Effects of Associatively Related Distractor Words

Table 2 illustrates mean RTs, mean error rates, and ex-Gaussian parameter estimates (μ , σ , τ) observed with associatively related and unrelated distractor words. Figure 3A shows the main results.

Initial analyses involving Session and Relatedness as factors revealed that associatively related distractor words sped up naming latencies compared with unrelated distractors ($F_1(1, 35) = 21.77, p < .001, \eta_p^2 = 0.38; F_2(1, 39) = 17.31,$

Figure 3. Results of the tDCS experiment. (A) Effects of a-tDCS stimulation on the associative facilitation effect. (B) Effects of a-tDCS stimulation on the SI effect. *** $p < .001$, ns = not significant.

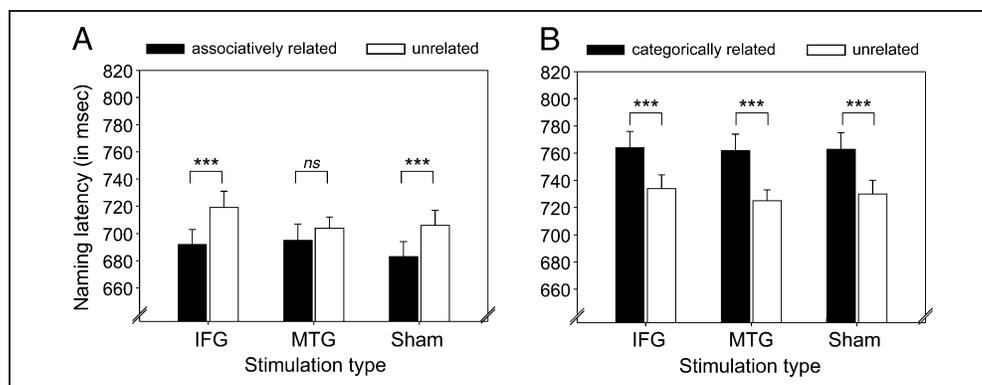
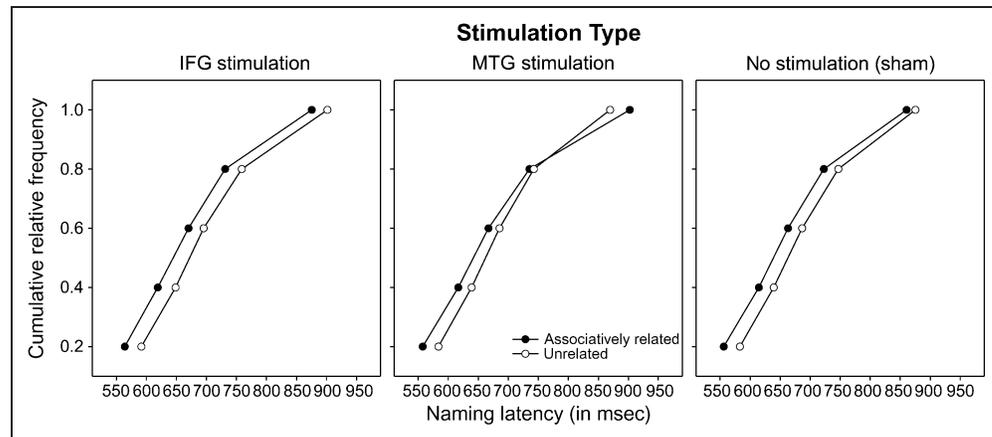


Figure 4. Vincentized cumulative distribution curves for the associatively related and unrelated condition, separated by stimulation type and relatedness.



$p < .001$, $\eta_p^2 = 0.31$). Mean naming latencies did not differ across sessions (699 msec, 702 msec, and 699 msec for Sessions 1–3, respectively; $F_s < 1$). There was no interaction of Relatedness and Session ($F_1(2, 70) = 1.42$, $p = .25$, $\eta_p^2 = 0.04$; $F_2(2, 78) = 1.90$, $p = .16$, $\eta_p^2 = 0.05$); in fact, associative facilitation effects were observed in each session (for Sessions 1–3: -14 msec, -20 msec, and -25 msec; all $p_s < .06$), suggesting sufficient sensitivity to the relatedness manipulation across sessions. In the analysis of error rates, there was no main effect of Relatedness ($F_s < 1$). Error rates decreased across sessions (3.4%, 2.5%, and 1.6% for Sessions 1–3; $F_1(2, 70) = 11.30$, $p < .001$, $\eta_p^2 = 0.24$; $F_2(2, 78) = 6.36$, $p < .01$, $\eta_p^2 = 0.14$), but there was no interaction of Relatedness and Session ($F_1(2, 70) = 1.73$, $p = .18$, $\eta_p^2 = 0.05$; $F_2(2, 78) = 1.49$, $p = .23$, $\eta_p^2 = 0.04$).

The main analyses involving the factors Relatedness and Stimulation Type again showed faster naming responses with associatively related distractor words (690 msec) than with unrelated distractor words (710 msec; $F_1(1, 35) = 21.77$, $p < .001$, $\eta_p^2 = 0.38$; $F_2(1, 39) = 17.38$, $p < .001$, $\eta_p^2 = 0.31$). Naming latencies differed slightly depending on stimulation (IFG: 706 msec, MTG: 700 msec, sham: 695 msec), but this effect was not significant in the participant analysis ($F_1(2, 70) = 1.90$, $p = .16$, $\eta_p^2 = 0.05$; $F_2(2, 78) = 8.99$, $p < .001$, $\eta_p^2 = 0.19$). Critically, there was an interaction between Stimulation and Relatedness ($F_1(2, 70) = 4.18$, $p < .02$, $\eta_p^2 = 0.11$; $F_2(1.5, 59.8) = 5.49$, $p < .05$, $\eta_p^2 = 0.12$), reflecting a reliable associative facilitation effect under IFG stimulation ($t_1(35) = 5.34$, $p < .001$; $t_2(39) = 4.95$, $p < .001$) and sham stimulation ($t_1(35) = 4.46$, $p < .001$; $t_2(39) = 3.94$, $p < .001$), but no such effect under MTG stimulation ($t_1(35) = 1.34$, $p = .19$; $t_2(39) = 1.47$, $p = .15$; see Figure 3A). There were no significant effects in the analyses of error rates (all $p_s > .19$).

An examination of the vincentized latency distribution curves (see Figure 4) suggests the absence of associative facilitation under MTG stimulation to be because of a reversal from associative facilitation for relatively fast responses to associative interference for relatively slow responses. Accordingly, analyses of the vincentized distributions showed a significant interaction of Quintile and

Relatedness under MTG stimulation ($F_1(1.4, 50.1) = 10.36$, $p < .001$, $\eta_p^2 = 0.23$; $F_2(1.4, 56.3) = 19.49$, $p < .001$, $\eta_p^2 = 0.33$). Under MTG stimulation, associative facilitation was observed for Quintiles 1–3 (all $p_s < .01$), no reliable effect was observed for Quintile 4 ($t_1 < 1$, $t_2(39) = 1.76$, $p = .09$), and associative interference was observed for Quintile 5 ($t_1(35) = 1.95$, $p = .06$; $t_2(39) = 2.78$, $p < .01$). By contrast, there was no interaction of Quintile and Relatedness under IFG and sham stimulations (all $F_s < 1$). This pattern of results is corroborated by analyses of the estimated ex-Gaussian parameters. There was a main effect of relatedness in the μ parameter ($F(1, 35) = 21.91$, $p < .001$, $\eta_p^2 = 0.39$), reflecting smaller μ with associatively related compared with unrelated distractor words, but no main effect of Relatedness in the σ or τ parameter (both $F_s < 1.1$). This suggests that the associative facilitation effect reflects a shift of the complete latency distribution toward faster responding with associatively related distractors. There was no effect of Stimulation Type in any of the three parameters (all $F_s < 1.2$) and also no interaction of Stimulation and Relatedness in the μ parameter and in the σ parameter ($p_s > .10$). Importantly, however, there was an interaction of stimulation and relatedness in the τ parameter ($F(2, 70) = 3.26$, $p < .05$, $\eta_p^2 = 0.09$). Although there was no difference between the τ parameters for associatively related and unrelated distractor words under IFG and sham stimulations ($p_s > .30$), τ were larger under MTG stimulation with associatively related (107 msec) compared with unrelated distractor words (82 msec, $t(35) = 2.06$, $p < .05$). Similar to the vincentile analyses, this suggests a shift from facilitation to interference at the tail of the latency distribution.

Effects of Categorically Related Distractor Words

Table 3 illustrates mean RTs, mean error rates, and ex-Gaussian parameter estimates (μ , σ , τ) observed with categorically related and unrelated distractor words. Figure 3B shows the main results.

Initial analyses involving Session and Relatedness as factors revealed that naming latencies were longer with

categorically related distractor words compared with unrelated distractor words ($F_1(1, 35) = 45.52, p < .001, \eta_p^2 = 0.57; F_2(1, 39) = 26.89, p < .001, \eta_p^2 = 0.41$). Overall, naming latencies decreased across sessions (754 msec, 747 msec, and 738 msec for Sessions 1–3; $F_1(2, 70) = 3.74, p < .05, \eta_p^2 = 0.10; F_2(1.7, 67.2) = 7.16, p = .01, \eta_p^2 = 0.16$), and there was an interaction between Session and Relatedness ($F_1(1.7, 59.0) = 3.53, p < .05, \eta_p^2 = 0.09; F_2(2, 78) = 3.51, p < .05, \eta_p^2 = 0.08$). However, there was substantial SI in each of the sessions (43 msec, 25 msec, and 33 msec for Sessions 1–3; all $ps < .001$), suggesting sufficient sensitivity to the relatedness manipulation across sessions. In correspondence to the effect on naming latencies, more errors were made with categorically related compared with unrelated distractor words ($F_1(1, 35) = 7.24, p < .05, \eta_p^2 = 0.17; F_2(1, 39) = 7.48, p < .01, \eta_p^2 = 0.16$). Error rates decreased across sessions (3.9%, 3.1%, and 2.1% for Sessions 1–3; $F_1(2, 70) = 8.71, p < .001, \eta_p^2 = 0.20; F_2(2, 78) = 6.37, p < .01, \eta_p^2 = 0.14$), but there was no interaction of relatedness and session in the analyses of error rates, $F_s < 1$.

The main analyses involving the factors Relatedness and Stimulation Type again showed that pictures were named slower in the presence of categorically related distractor words (763 msec) compared with unrelated distractor words (729 msec; $F_1(1, 35) = 45.52, p < .001, \eta_p^2 = 0.57; F_2(1, 39) = 27.19, p < .001, \eta_p^2 = 0.41$). There was

no main effect of Stimulation ($F_1 < 1, F_2(2, 78) = 1.63, p = .20, \eta_p^2 = 0.04$) and no interaction between these factors ($F_s < 1$; Figure 3B). The analyses of error rates revealed that more errors were made with categorically related distractor words (3.6%) compared with unrelated distractor words (2.4%; $F_1(1, 35) = 7.24, p < .05, \eta_p^2 = 0.17; F_2(1, 39) = 7.48, p < .01, \eta_p^2 = 0.16$). But there was no effect of stimulation and no interaction of stimulation and relatedness (all $F_s < 1$).

Examination of the vincentized latency distributions (see Figure 5) shows that SI increased with increasing naming latencies under all stimulation types. This is exemplified by a significant interaction of quintile and relatedness for all stimulations (all $ps < .001$). However, although SI increased in size across the distribution, it was not restricted to the tail of the distribution. Under IFG and sham stimulation, SI was significant throughout the complete distribution (for Quintiles 1–5, all $ps < .06$); under MTG stimulation, the SI effect was significant for Quintiles 2–5 ($ps < .05$) but not significant in Quintile 1 ($ps > .14$). Analyses of the estimated ex-Gaussian parameters showed that the SI effect was reflected in larger τ with categorically related (126 msec) compared with unrelated distractors (94 msec; $F(1, 35) = 12.23, p < .01, \eta_p^2 = 0.26$), whereas there was no main effect of Relatedness in the μ and σ parameters ($F_s < 1$). This suggests that the SI effect in our study appears to be most prominently

Table 3. Results for Categorically Related Distractors

	<i>RT</i>	%	μ	σ	τ
<i>IFG Stimulation</i>					
Categorically related	764 (12)	3.6 (0.6)	657 (11)	65 (8)	107 (11)
Unrelated	734 (10)	2.0 (0.5)	646 (10)	55 (6)	88 (8)
Difference	30*** (7)	1.6 (0.5)	11 (9)	10 (8)	19 (11)
<i>MTG Stimulation</i>					
Categorically related	762 (12)	3.7 (0.7)	625 (9)	42 (6)	140 (13)
Unrelated	725 (8)	2.8 (0.5)	634 (10)	52 (4)	89 (11)
Difference	37*** (7)	0.9 (0.7)	–9 (9)	–10 (9)	51** (15)
<i>No Stimulation (Sham)</i>					
Categorically related	763 (12)	3.6 (0.7)	635 (11)	47 (6)	131 (12)
Unrelated	730 (10)	2.5 (0.5)	625 (9)	39 (5)	106 (8)
Difference	33*** (6)	1.1 (0.5)	10 (9)	8 (7)	25* (11)

Mean naming latencies (in msec), errors rates (in percent), and ex-Gaussian parameters (μ , σ , τ) for the semantically related and unrelated conditions, separated by stimulation location and relatedness.

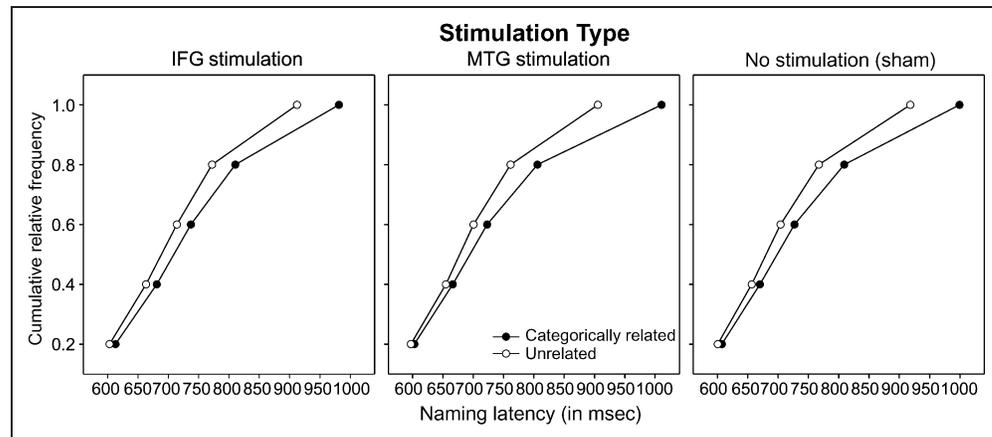
Standard errors of the mean are given in parentheses.

* $p < .05$.

** $p < .01$.

*** $p < .001$.

Figure 5. Vincentized cumulative distribution curves for the categorically related and unrelated conditions, separated by stimulation type and relatedness.



reflected by an increased distributional skew (i.e., increasing in size with slower responses), not by a complete shift of the distribution. There was a main effect of Stimulation in the μ parameter ($F(2, 70) = 4.40, p < .05, \eta_p^2 = 0.11$), reflecting an increase in the μ parameter under IFG stimulation (651 msec) compared with MTG (630 msec) and sham stimulations (630 msec). Pairwise comparisons (Bonferroni-corrected) revealed only the contrast between IFG and MTG stimulation to be significant ($p < .05$, other contrasts: $ps > .09$). There was also a main effect of stimulation in the σ parameter ($F(1.6, 56.3) = 3.53, p < .05, \eta_p^2 = 0.09$), reflecting an increased σ parameter under IFG stimulation (60 msec) compared with MTG (47 msec) and sham stimulations (43 msec), but pairwise comparisons (Bonferroni-corrected) were not significant ($ps > .11$). There was no reliable main effect of Stimulation on the τ parameter, $F(1, 35) = 2.60, p = .08, \eta_p^2 = 0.07$, and no reliable interaction between Relatedness and Stimulation in any parameter (all $ps > .09$).

DISCUSSION

The current study was designed to shed further light on the processes that shape lexico-semantic selection during word production. For this purpose, the PWI paradigm was used creating a situation of high or low selection demands by the presence of categorically or associatively related distractors, respectively. During performance of the PWI paradigm, the activity of either a frontal or a temporal brain region was modulated with a-tDCS to explore the specific function of these regions during the selection process. In particular, we addressed the following questions: (1) If the left pMTG is involved in the retrieval of lexico-semantic information and associative priming, as described previously (see, e.g., Whitney et al., 2011; Gold et al., 2006; Badre et al., 2005; Wagner et al., 2001), then does a-tDCS over this region lead to changed usage of the information provided by associatively related primes? (2) If the left IFG is involved in the selection of lexico-semantic information from a set of competing

alternatives, as has been proposed before (see, e.g., Snyder et al., 2007; Badre et al., 2005; Thompson-Schill et al., 1997), then does a-tDCS over this region influence the SI effect induced by categorically related distractors?

First of all, the data reveal that the experimental selection demand manipulation worked well. Throughout all sessions, there was a strong SI with categorically related distractors (33 msec) and a strong and stable facilitation effect with associatively related distractors (20 msec). Critically, there was a significant interaction between tDCS stimulation and the associative effects. In particular, the associative facilitation effect was present under IFG and sham stimulations but diminished under MTG stimulation. Analyses of latency distributions suggest that this was because of a reversal from associative facilitation for faster responses to associative interference with slower responses under MTG stimulation. In contrast to the associative facilitation effect, there was no modulation of the SI effect because of the tDCS stimulation.

The left temporal target region that we stimulated (MNI coordinates: $-56, -48, -2$) has been implicated in a number of previous fMRI studies to be related to semantic retrieval (MNI: $-57, -51, 0$; Wagner et al., 2001; $-48, -48, 3$; Badre et al., 2005), semantic priming (MNI: $-54, -45, -2$; Gold et al., 2006), semantic selection (MNI: $-57, -48, -3$; Snyder et al., 2007), and ambiguity resolution (MNI: $-57, -42, -3$; Bedny et al., 2008). It has further been described that virtual lesioning of this region with TMS affects the “controlled retrieval and selection of semantic information” (MNI: $-56, -50, -3$; Whitney et al., 2011). Moreover, the pMTG seems to be involved in processes of “semantic integration” as seen with the cloze paradigm (semantically expected vs. unexpected sentence endings, Obleser & Kotz, 2010; Baumgaertner, Weiller, & Buchel, 2002), and the brain area is often lesioned in patients with semantic control deficits (Noonan, Jefferies, Corbett, & Lambon Ralph, 2010). In language models, the region has been hypothesized to form a convergence zone that plays a “mediational role in lexical retrieval,” (Damasio, Tranel, Grabowski, Adolphs, &

Damasio, 2004), to represent a “lexical interface” (Hickok, Houde, & Rong, 2011) or the neural counterpart of the lemma level (Indefrey & Levelt, 2004; Levelt, 1992, 1999). Thus, the literature provides strong evidence that the left pMTG is related to the access and retrieval of the correct lexico-semantic entry. However, it has not yet been tested which effect an excitatory stimulation of this brain region may have.

The current study provides this test. We stimulated the left pMTG with a-tDCS over 20 min during performance of the PWI task (on-line stimulation protocol). The observed modulation of the associative facilitation effect under MTG stimulation adds to the available evidence that activation in this region is connected to associative priming effects (cf. Abel et al., 2009). Interestingly, however, this stimulation did not lead to a better usage of priming information during picture naming, as one could have expected, but rather produced an adverse effect, a reduction of the associative facilitation effect. This is an unexpected finding, because a-tDCS is supposed to increase cortical excitability (depolarization of neurons, see Nitsche & Paulus, 2000). One explanation of this result may be that the MTG stimulation induced a high activation level in the lexicon, creating a situation in which preactivation of the target entry by an associative prime did not have a beneficial effect anymore because of the already-enhanced activation. In other words, we may have induced unspecific “noise” in the system, which might have masked more subtle differential activation patterns caused by related and unrelated distractor words. This situation could be roughly comparable with the situation of “lexical overactivation,” as proposed by McNellis and Blumstein (2001) in their model of aphasia. According to this model, Wernicke’s aphasia can be characterized as a situation of overactivation in the lexicon (or alternatively insufficient inhibition), leading to impaired selection of the target word.

However, taking a closer look at the data, an explanation in terms of overactivation in itself does not provide a ready explanation for the apparent reversal from associative facilitation to associative interference under MTG stimulation across the latency distribution. This distribution pattern suggests that the associative facilitation effect under MTG stimulation might not have been generally prevented by the MTG stimulation but that it was overriden by an interference effect for slower responses. The observation might be connected to the results of a recent study by Pisoni, Papagno, and Cattaneo (2012), who reported that a-tDCS applied over the left superior temporal gyrus (STG) leads to worse performance in a blocked naming paradigm. In this paradigm, participants are typically getting slower in naming a row of pictures presented in homogeneous sets (coming from the same semantic category) compared with naming pictures in heterogeneous sets. This interference effect was increased by a-tDCS stimulation. Although this effect might not be directly comparable with the effects seen in the PWI paradigm, the explanatory accounts for their and our results

may be comparable. Pisoni et al. (2012) suggested that the tDCS stimulation “increased lexical activation for a prolonged period, thus enhancing the competition among stimuli in semantically related clusters.”

This explanation is related to an account of SI and facilitation effects in the PWI task by Abdel Rahman and Melinger (2009). They argued that interference effects because of lexical competition can only be observed in a situation in which competitor activation cumulates over a cohort of highly interconnected representations, whereas facilitation effects are observed when the cumulation of competitor activation is not sufficient to outweigh facilitative priming effects (see also Roelofs, Piai, & Schriefers, 2011, for a related account assuming a competition threshold). In particular, semantically related (i.e., category coordinate) distractors are argued to cause behavioral interference effects because they trigger the mutual coactivation of highly interconnected semantic cohort. In contrast, associatively related distractors are argued to cause facilitation effects, because associatively related target and distractor representations share only few connections to other representations, and therefore, the cumulation of competing activation in the lexical system might not be sufficient to induce substantial competitive interference effects. Importantly, facilitative priming and interfering competition mechanisms are not necessarily mutually exclusive under this account. Instead, the relative contributions of facilitative processes (e.g., because of priming) and interfering processes (e.g., because of competition) determine the direction of the behavioral net effects. Adopting this view might provide an explanation for the reversal from associative facilitation to associative interference under MTG stimulation in our study. Increasing the excitability of representations in the lexico-semantic network might have promoted a sufficient cumulation of competing activation even along the fewer connections between associatively related representations. Thus, the reversal from associative facilitation to associative interference might reflect that under MTG stimulation, on some trials, competing coactivation was increased enough to reveal competitive selection processes. The overall null effect of associatively related distractors under MTG stimulation would then reflect a mixture of trials in which facilitation because of priming outweighed interference because of competition and vice versa. Similarly, one might also argue that unspecific “overactivation” because of MTG stimulation reduced facilitative priming (see above) on some trials to the extent that underlying interfering processes became visible.

Of course, this account would also predict an increase in SI under MTG stimulation. However, the stimulation of left pMTG interfered with the associative priming effect but had no reliable effect on the SI effect induced by categorically related distractors. Consequently, one might speculate that the processes underlying the SI effect are not directly related to the left pMTG, whereas the processes underlying associative priming are related to this

brain region. Pisoni et al. (2012) found an increased semantic blocking effect when applying a-tDCS over the left STG, not the left MTG. This may implicate that these two temporal brain regions are differentially sensitive to certain aspects of semantic selection, with SI effects being more related to the left STG and the effects of associative priming being more related to the left pMTG. We want to note, however, that the SI effect (as reflected in the τ parameters) was descriptively also increased under MTG stimulation (51 msec) compared with IFG stimulation (19 msec) and sham stimulation (25 msec), and therefore, the conclusion that MTG stimulation did not affect SI effects at all might be premature. Clearly, this issue is in need of further investigation in subsequent studies.

Another brain region that has often been suggested to be crucially involved in semantic selection during word production is the left inferior frontal cortex. The IFG region stimulated in the current study (center of stimulation at MNI coordinates of $-50, 15, 29$) has been found in fMRI studies to be related to the “controlled retrieval of semantic information” (reported MNI coordinates: $-51, 18, 27$; Wagner et al., 2001), “retrieval and selection demands” (MNI: $-51, 15, 33$; Badre et al., 2005), the “selection of semantic information among competing sources of information” (MNI: $-49, 8, 30$; Thompson-Schill et al., 1997), semantic competitor priming (MNI: $-54, 4, 24$; Moss et al., 2005), ambiguity resolution (MNI: $-54, 9, 39$; Bedny et al., 2008), and semantic blocking (MNI: $-51, 9, 39$; Schnur et al., 2009). On the basis of this information, we chose the left IFG as our second target region and expected that its excitatory stimulation may influence the SI effect.

However, surprisingly, the stimulation of left IFG with a-tDCS did not have any effect on the SI effect, that is, the effect did not differ between IFG, MTG, and sham stimulations. This result is surprising because we predicted that facilitatory stimulation of the left IFG may reduce the SI effect induced by categorically related distractors. This, however, would imply two things: (1) that the stimulated brain region is sensitive to the categorical relation between target and distractor and (2) that the modulation of this region with a-tDCS critically influences this involvement. Accordingly, one possible explanation for the current finding is that the stimulated region is not directly sensitive to the categorical relation between target and distractor. In using the IFG coordinates provided by the meta-analysis, the target region was located in the posterior superior portion of the left IFG, next to the inferior frontal junction (IFJ). Although there are a lot of studies implicating this region in the selection among competing alternatives, its main function may be that of a top-down influence in situations of high selection demands. Accordingly, the IFG/IFJ has been suggested to be crucial for processes such as filtering out irrelevant information, conflict detection, or allocating attention to task-relevant information (see, e.g., de Zubicaray et al., 2001, 2006; Schnur, Schwartz, Brecher, & Hodgson, 2006; Schnur, Lee, Coslett, Schwartz, & Thompson-Schill,

2005; Roelofs, 2003). Wagner et al. (2001, p. 329) stated that “left inferior frontal cortex mediates a top-down bias signal that is recruited to the extent that the recovery of meaning demands controlled retrieval.” The observed involvement of this region in a number of studies on semantic selection might thus be rather related to controlled top-down processes that are extrinsic to the mental lexicon than to processes working directly within the lexicon, which are supposed to underlie the SI effect in the PWI paradigm.

Remarkably, most paradigms used in former studies on SI worked with relatively slow time scales and thus allowed for such controlled (and explicit) processing. For instance, in the semantic competitor priming paradigms used by de Zubicaray et al. (2006) and Moss et al. (2005), the time between the presentation of the competing/distracting information and the target picture was several seconds, and in the semantic blocking paradigms used by Pisoni et al. (2012), Wirth et al. (2011), and Schnur et al. (2009), the blocking effect was build up over seconds. These time scales support controlled processing, and this might be one reason for the beneficial effect of frontal a-tDCS stimulation on the semantic blocking effect (see Pisoni et al., 2012; Wirth et al., 2011). In contrast, the PWI paradigm and cueing paradigms induce interference in a very fast (millisecond range) and not controllable (implicit) manner and may thus affect different processes. In accordance with this assumption, Holland et al. (2011) observed no differential effect of a-tDCS stimulation over the left IFS/IFG on different cueing conditions (same word vs. noise cue) in a picture naming task. Thus, taken together, there is some evidence that facilitatory tDCS stimulation over the left IFG supports the resolution of competition in word production, but this intervention appears to primarily support processes that act on larger time scales and work in a controlled fashion. In contrast, the PWI paradigm works on a significantly faster time scale, and these fast, “lexicon-near” processes may not be influenced by facilitatory stimulation of the posterior IFG/IFJ.

Conclusions

Taken together, the results of the current study support the view that the SI and associative facilitation effect are linked to differential activation in the pMTG. Stimulation of this brain region with a-tDCS led to diminishment of the associative facilitation effect, either because of an unspecific overactivation in the lexicon or by promoting competition among associatively related representations, whereas it had no reliable influence on the categorical interference effect. This suggests that the pMTG is especially involved in the processes underlying associative priming but may also be related to processes causing interference effects in the PWI paradigm. The stimulation of the left frontal target region, in contrast, had no effect on behavioral performance in any condition. This may suggest that the previously described involvement of this

region in semantic selection seems to be more related to controlled top-down processes biasing lexical selection than to the lexicon-near processes tested in the PWI paradigm. Apart from its implications for basic research, these results have also consequences for the clinical use of tDCS in the neurorehabilitation of aphasia. The current data suggest that the left pMTG is an important brain region to support facilitatory effects during word retrieval in speech production and that the left IFG may be involved in controlled lexico-semantic selection. In further tDCS studies, the effects of different stimulation modalities on these brain regions in patients with aphasia can be tested. Especially, cathodal stimulation of pMTG may be beneficial when the lexicon is overactivated. Consequently, this may help to develop new therapeutic strategies in aphasia.

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Note

1. Pretests ($n = 56$) using slightly different materials than in this study and testing SOAs from -300 to 0 msec revealed associative facilitation effects at SOAs of -300 and -200 msec and categorical interference effects at SOAs of -100 and 0 msec, with the strongest effects at -300 and -100 msec, respectively. A final pretest ($n = 12$) using the same materials as in this study revealed reliable associative facilitation effects with SOA of -300 msec (-20 msec, $ps < .05$) and categorical interference at SOA of -100 msec (56 msec, $ps < .01$).

REFERENCES

- Abdel Rahman, R. A., & Melinger, A. (2009). Semantic context effects in language production: A swinging lexical network proposal and a review. *Language and Cognitive Processes, 24*, 713–734.
- Abel, S., Dressel, K., Bitzer, R., Kummerer, D., Mader, I., Weiller, C., et al. (2009). The separation of processing stages in a lexical interference fMRI-paradigm. *Neuroimage, 44*, 1113–1124.
- Alario, F. X., Segui, J., & Ferrand, L. (2000). Semantic and associative priming in picture naming. *Quarterly Journal of Experimental Psychology: Section A—Human Experimental Psychology, 53*, 741–764.
- Badre, D., Poldrack, R. A., Pare-Blagoev, E. J., Inslar, R. Z., & Wagner, A. D. (2005). Dissociable controlled retrieval and generalized selection mechanisms in ventrolateral prefrontal cortex. *Neuron, 47*, 907–918.
- Baumgaertner, A., Weiller, C., & Buchel, C. (2002). Event-related fMRI reveals cortical sites involved in contextual sentence integration. *Neuroimage, 16*, 736–745.
- Bedny, M., McGill, M., & Thompson-Schill, S. L. (2008). Semantic adaptation and competition during word comprehension. *Cerebral Cortex, 18*, 2574–2585.
- Berg, T., & Schade, U. (1992). The role of inhibition in a spreading-activation model of language production: 1. The psycholinguistic perspective. *Journal of Psycholinguistic Research, 21*, 405–434.
- Brown, S., & Heathcote, A. (2003). QMLE: Fast, robust, and efficient estimation of distribution functions based on quantiles. *Behavior Research Methods, Instruments, & Computers, 35*, 485–492.
- Caramazza, A. (1997). How many levels of processing are there in lexical access? *Cognitive Neuropsychology, 14*, 177–208.
- Caramazza, A., & Hillis, A. E. (1990). Where do semantic errors come from? *Cortex, 26*, 95–122.
- Collins, A. M., & Loftus, E. F. (1975). Spreading activation theory of semantic processing. *Psychological Review, 82*, 407–428.
- Corbett, F., Jefferies, E., & Ralph, M. A. L. (2011). Deregulated semantic cognition follows prefrontal and temporo-parietal damage: Evidence from the impact of task constraint on nonverbal object use. *Journal of Cognitive Neuroscience, 23*, 1125–1135.
- Costa, A., Alario, F. X., & Caramazza, A. (2005). On the categorical nature of the semantic interference effect in the picture-word interference paradigm. *Psychonomic Bulletin & Review, 12*, 125–131.
- Damasio, H., Tranel, D., Grabowski, T., Adolphs, R., & Damasio, A. (2004). Neural systems behind word and concept retrieval. *Cognition, 92*, 179–229.
- Damian, M. F., & Martin, R. C. (1999). Semantic and phonological codes interact in single word production. *Journal of Experimental Psychology: Learning Memory and Cognition, 25*, 345–361.
- de Zubicaray, G. I., & McMahon, K. L. (2009). Auditory context effects in picture naming investigated with event-related fMRI. *Cognitive Affective & Behavioral Neuroscience, 9*, 260–269.
- de Zubicaray, G., McMahon, K., Eastburn, M., Pringle, A., & Stephansen, J. (2006). Refractory effects in picture naming: An fMRI investigation of semantic competitor priming. *Journal of Psychophysiology, 20*, 335–336.
- de Zubicaray, G. I., Wilson, S. J., McMahon, K. L., & Muthiah, S. (2001). The semantic interference effect in the picture-word task: An event-related fMRI study employing overt responses. *Human Brain Mapping, 14*, 218–227.
- Dell, G. S. (1986). A spreading-activation theory of retrieval in sentence production. *Psychological Review, 93*, 283–321.
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual-attention. *Annual Review of Neuroscience, 18*, 193–222.
- Eickhoff, S. B., Laird, A. R., Grefkes, C., Wang, L. E., Zilles, K., & Fox, P. T. (2009). Coordinate-based activation likelihood estimation meta-analysis of neuroimaging data: A random-effects approach based on empirical estimates of spatial uncertainty. *Human Brain Mapping, 30*, 2907–2926.
- Finkbeiner, M., & Caramazza, A. (2006). Lexical selection is not a competitive process: A reply to La Heij et al. (2006). *Cortex, 42*, 1032–1036.
- Garrett, M. F. (1992). Disorders of lexical selection. *Cognition, 42*, 143–180.
- Glaser, W. R., & Dungenhoff, F. J. (1984). The time course of picture word interference. *Journal of Experimental Psychology: Human Perception and Performance, 10*, 640–654.
- Gold, B. T., Balota, D. A., Jones, S. J., Powell, D. K., Smith, C. D., & Andersen, A. H. (2006). Dissociation of automatic

- and strategic lexical-semantics: Functional magnetic resonance imaging evidence for differing roles of multiple frontotemporal regions. *Journal of Neuroscience*, *26*, 6523–6532.
- Goldrick, M. (2007). Cognitive constraints on distributed neural representations: Insights from connectionist networks. *Brain and Language*, *103*, 164–165.
- Hantsch, A., Jescheniak, J. D., & Schriefers, H. (2005). Semantic competition between hierarchically related words during speech planning. *Memory and Cognition*, *33*, 984–1000.
- Hantsch, A., Jescheniak, J. D., & Schriefers, H. (2009). Distractor modality can turn semantic interference into semantic facilitation in the picture–word interference task: Implications for theories of lexical access in speech production. *Journal of Experimental Psychology: Learning Memory and Cognition*, *35*, 1443–1453.
- Harley, T. A., Jones, G. V., Dunbar, G. L., & Macandrew, S. B. G. (1995). From meaning to sound—Serial order from parallel systems. *Language and Cognitive Processes*, *10*, 383–386.
- Heathcote, A., Brown, S., & Cousineau, D. (2004). QMPE: Estimating Lognormal, Wald, and Weibull RT distributions with a parameter-dependent lower bound. *Behavior Research Methods, Instruments, & Computers*, *36*, 277–290.
- Heim, S., Eickhoff, S. B., Friederici, A. D., & Amunts, K. (2009). Left cytoarchitectonic area 44 supports selection in the mental lexicon during language production. *Brain Structure and Function*, *213*, 441–456.
- Heister, J., Würzner, K. M., Bubbenzer, J., Pohl, E., Hanneforth, T., Geyken, A., et al. (2011). dlexDB—eine lexikalische Datenbank für die psychologische und linguistische Forschung. *Psychologische Rundschau*, *62*, 10–20.
- Hickok, G., Houde, J., & Rong, F. (2011). Sensorimotor integration in speech processing: Computational basis and neural organization. *Neuron*, *69*, 407–422.
- Holland, R., Leff, A. P., Josephs, O., Galea, J. M., Desikan, M., Price, C. J., et al. (2011). Speech facilitation by left inferior frontal cortex stimulation. *Current Biology*, *21*, 1403–1407.
- Houghton, G., & Tipper, S. P. (1996). Inhibitory mechanisms of neural and cognitive control: Applications to selective attention and sequential action. *Brain and Cognition*, *30*, 20–43.
- Indefrey, P., & Levelt, W. J. M. (2004). The spatial and temporal signatures of word production components. *Cognition*, *92*, 101–144.
- Jefferies, E., & Lambon Ralph, M. A. (2006). Semantic impairment in stroke aphasia versus semantic dementia: A case-series comparison. *Brain*, *129*, 2132–2147.
- Kan, I. P., & Thompson-Schill, S. L. (2004). Selection from perceptual and conceptual representations. *Cognitive, Affective & Behavioral Neuroscience*, *4*, 466–482.
- Kuperberg, G. R., Lakshmanan, B. M., Greve, D. N., & West, W. C. (2008). Task and semantic relationship influence both the polarity and localization of hemodynamic modulation during lexico-semantic processing. *Human Brain Mapping*, *29*, 544–561.
- Lau, E. F., Phillips, C., & Poeppel, D. (2008). A cortical network for semantics: (De)constructing the N400. *Nature Reviews Neuroscience*, *9*, 920–933.
- Levelt, W. J. M. (1992). Accessing words in speech production—Stages, processes and representations. *Cognition*, *42*, 1–22.
- Levelt, W. J. M. (1999). Models of word production. *Trends in Cognitive Sciences*, *3*, 223–232.
- Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences*, *22*, 1–38.
- Mädebach, A., Oppermann, F., Babeliowsky, L., & Jescheniak, J. D. (2013). A new German picture database: Naming and recognition latencies for a set of 520 pictures [Abstract]. In U. Ansorge, E. Kirchner, C. Lamm, & H. Leder (Eds.), *Abstracts of the 55. Conference of experimental psychologists* (p. 391). Lengerich: Pabst.
- Mahon, B. Z., Costa, A., Peterson, R., Vargas, K. A., & Caramazza, A. (2007). Lexical selection is not by competition: A reinterpretation of semantic interference and facilitation effects in the picture–word interference paradigm. *Journal of Experimental Psychology: Learning Memory and Cognition*, *33*, 503–535.
- McNellis, M. G., & Blumstein, S. E. (2001). Self-organizing dynamics of lexical access in normals and aphasics. *Journal of Cognitive Neuroscience*, *13*, 151–170.
- Melinger, A., & Weber, A. (2006). *Database of noun associations for German*. <http://www.coli.uni-saarland.de/projects/nag/>.
- Minhas, P., Bansal, V., Patel, J., Ho, J. S., Diaz, J., Datta, A., et al. (2010). Electrodes for high-definition transcutaneous DC stimulation for applications in drug delivery and electrotherapy, including tDCS. *Journal of Neuroscience Methods*, *190*, 188–197.
- Moss, H. E., Abdallah, S., Fletcher, P., Bright, P., Pilgrim, L., Acres, K., et al. (2005). Selecting among competing alternatives: Selection and retrieval in the left inferior frontal gyrus. *Cerebral Cortex*, *15*, 1723–1735.
- Nagel, I. E., Schumacher, E. H., Goebel, R., & D’Esposito, M. (2008). Functional MRI investigation of verbal selection mechanisms in lateral prefrontal cortex. *Neuroimage*, *43*, 801–807.
- Nitsche, M. A., & Paulus, W. (2000). Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *Journal of Physiology-London*, *527*, 633–639.
- Noonan, K. A., Jefferies, E., Corbett, F., & Lambon Ralph, M. A. (2010). Elucidating the nature of deregulated semantic cognition in semantic aphasia: Evidence for the roles of prefrontal and temporo-parietal cortices. *Journal of Cognitive Neuroscience*, *22*, 1597–1613.
- Obleser, J., & Kotz, S. A. (2010). Expectancy constraints in degraded speech modulate the language comprehension network. *Cerebral Cortex*, *20*, 633–640.
- Piai, V., Roelofs, A., & Schriefers, H. (2011). Semantic interference in immediate and delayed naming and reading: Attention and task decisions. *Journal of Memory and Language*, *64*, 404–423.
- Piai, V., Roelofs, A., & Schriefers, H. (2012). Distractor strength and selective attention in picture-naming performance. *Memory & Cognition*, *40*, 614–627.
- 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.
- Posner, M. I., & Snyder, C. R. R. (1975). Facilitation and inhibition in the processing of signals. In P. M. A. Rabbitt & S. Dornic (Eds.), *Attention and performance V* (pp. 669–681). New York: Academic Press.
- Rapp, B., & Goldrick, M. (2000). Discreteness and interactivity in spoken word production. *Psychological Review*, *107*, 460–499.
- Ratcliff, R. (1979). Group reaction time distributions and an analysis of distribution statistics. *Psychological Bulletin*, *86*, 446–461.
- Righi, G., Blumstein, S. E., Mertus, J., & Worden, M. S. (2010). Neural systems underlying lexical competition: An eye tracking and fMRI study. *Journal of Cognitive Neuroscience*, *22*, 213–224.
- Roelofs, A. (1992). A spreading-activation theory of lemma retrieval in speaking. *Cognition*, *42*, 107–142.

- Roelofs, A. (1997). The WEAVER model of word-form encoding in speech production. *Cognition*, *64*, 249–284.
- Roelofs, A. (2003). Goal-referenced selection of verbal action: Modelling attentional control in the Stroop task. *Psychological Review*, *110*, 88–125.
- Roelofs, A. (2008). Dynamics of the attentional control of word retrieval: Analyses of response time distributions. *Journal of Experimental Psychology: General*, *137*, 303–323.
- Roelofs, A., Piai, V., & Schriefers, H. (2011). Selective attention and distractor frequency in naming performance: Comment on Dhooge and Hartsuiker (2010). *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *37*, 1032–1038.
- Sailor, K., Brooks, P. J., Bruening, P. R., Seiger-Gardner, L., & Guterman, M. (2009). Exploring the time course of semantic interference and associative priming in the picture–word interference task. *Quarterly Journal of Experimental Psychology*, *62*, 789–801.
- Schnur, T. T., Lee, E., Coslett, H. B., Schwartz, M. F., & Thompson-Schill, S. L. (2005). When lexical selection gets tough, the LIFG gets going: A lesion analysis study of interference during word production. *Brain and Language*, *95*, 12–13.
- Schnur, T. T., Schwartz, M. F., Brecher, A., & Hodgson, C. (2006). Semantic interference during blocked-cyclic naming: Evidence from aphasia. *Journal of Memory and Language*, *54*, 199–227.
- Schnur, T. T., Schwartz, M. F., Kimberg, D. Y., Hirshorn, E., Coslett, H. B., & Thompson-Schill, S. L. (2009). Localizing interference during naming: Convergent neuroimaging and neuropsychological evidence for the function of Broca's area. *Proceedings of the National Academy of Sciences, U.S.A.*, *106*, 322–327.
- Schriefers, H., Meyer, A. S., & Levelt, W. J. M. (1990). Exploring the time course of lexical access in language production—Picture–word interference studies. *Journal of Memory and Language*, *29*, 86–102.
- Snyder, H. R., Feigenson, K., & Thompson-Schill, S. L. (2007). Prefrontal cortical response to conflict during semantic and phonological tasks. *Journal of Cognitive Neuroscience*, *19*, 761–775.
- Spalek, K., & Thompson-Schill, S. L. (2008). Task-dependent semantic interference in language production: An fMRI study. *Brain and Language*, *107*, 220–228.
- Starreveld, P. A., & LaHeij, W. (1996). Time-course analysis of semantic and orthographic context effects in picture naming. *Journal of Experimental Psychology: Learning Memory and Cognition*, *22*, 896–918.
- Thompson-Schill, S. L., D'Esposito, M., Aguirre, G. K., & Farah, M. J. (1997). Role of left inferior prefrontal cortex in retrieval of semantic knowledge: A reevaluation. *Proceedings of the National Academy of Sciences, U.S.A.*, *94*, 14792–14797.
- Thompson-Schill, S. L., D'Esposito, M., & Kan, I. P. (1999). Effects of repetition and competition on activity in left prefrontal cortex during word generation. *Neuron*, *23*, 513–522.
- Turkeltaub, P. E., Eden, G. F., Jones, K. M., & Zeffiro, T. A. (2002). Meta-analysis of the functional neuroanatomy of single-word reading: Method and validation. *Neuroimage*, *16*, 765–780.
- Wagner, A. D., Pare-Blagoev, E. J., Clark, J., & Poldrack, R. A. (2001). Recovering meaning: Left prefrontal cortex guides controlled semantic retrieval. *Neuron*, *31*, 329–338.
- Wheeldon, L. R., & Monsell, S. (1994). Inhibition of spoken word production by priming a semantic competitor. *Journal of Memory and Language*, *33*, 332–356.
- Whitney, C., Grossman, M., & Kircher, T. T. J. (2009). The influence of multiple primes on bottom–up and top–down regulation during meaning retrieval: Evidence for 2 distinct neural networks. *Cerebral Cortex*, *19*, 2548–2560.
- Whitney, C., Kirk, M., O'Sullivan, J., Ralph, M. A. L., & Jefferies, E. (2011). The neural organization of semantic control: TMS evidence for a distributed network in left inferior frontal and posterior middle temporal gyrus. *Cerebral Cortex*, *21*, 1066–1075.
- Whitney, C., Kirk, M., O'Sullivan, J., Ralph, M. A. L., & Jefferies, E. (2012). Executive semantic processing is underpinned by a large-scale neural network: Revealing the contribution of left prefrontal, posterior temporal, and parietal cortex to controlled retrieval and selection using TMS. *Journal of Cognitive Neuroscience*, *24*, 133–147.
- Wilshire, C. E., & McCarthy, R. A. (2002). Evidence for a context-sensitive word retrieval disorder in a case of nonfluent aphasia. *Cognitive Neuropsychology*, *19*, 165–186.
- Wirth, M., Rahman, R. A., Kuenecke, J., Koenig, T., Horn, H., Sommer, W., et al. (2011). Effects of transcranial direct current stimulation (tDCS) on behaviour and electrophysiology of language production. *Neuropsychologia*, *49*, 3989–3998.