



## Effects of tDCS applied over Broca's and Wernicke's areas on verb recognition task performance

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Keywords:	Anodal direct current stimulation, Broca's area, Reaction time, Verbal recognition, verb category, Wernicke's area
Abstract:	<p><b>Abstract</b></p> <p>Objectives: Beyond their primary roles in motor aspects, and sensory perception of language, Broca's and Wernicke's areas have been recently associated with broader language functions, such as processing of action words for Broca's area and an involvement of Wernicke's area in recognition of different word categories. Knowledge about the relevance of these areas for respective functions is however limited at present. tDCS is a non-invasive brain stimulation method that alters cortical activity and excitability, and thus might be a useful tool for delineating the specific impact of both areas on word recognition. The objective of this study was to explore whether the visual recognition process of verb categories is improved by a single tDCS session. Methods: Broca's and Wernicke's areas, defined as the anatomical regions of the left inferior frontal gyrus (IIFG) and left posterior superior temporal gyrus (IpSTG), respectively, were separately modulated by anodal tDCS (1.5 mA current strength) to evaluate its effects on verbal recognition. Results: Compared to sham stimulation, reaction times (RTs) were reduced after IpSTG anodal tDCS, and this effect was independent of the type of verb used in the verbal task (movement, emotional and neutral verbs) and performing hand (right or left). Anodal tDCS over the IIFG reduced RTs only trend-wise. Conclusions: These findings suggest that the IpSTG region is involved in word recognition independently from the verb category and performing hand. The contribution of the IIFG to this verbal function is, however, uncertain.</p> <p>Keywords: Broca's area, Reaction time, verbalrecognition, verbs category, Wernicke 's area.</p>

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**IMPACT STATEMENTS**

\*The involvement of Wernicke's and Broca's area to verb recognition is uncertain

\*The specific contribution of these areas to visual recognition of verb categories was compared via tDCS application

\*This study shows for the first time that neuromodulation of Wernicke's area, but not Broca's area, improves the verb recognition process

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3 **Effects of tDCS applied over Broca's and Wernicke's areas on verb recognition**  
4 **task performance**  
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## Abstract

**Objectives:** Beyond their primary roles in motor aspects, and sensory perception of language, Broca's and Wernicke's areas have been recently associated with broader language functions, such as processing of action words for Broca's area and an involvement of Wernicke's area in recognition of different word categories. Knowledge about the relevance of these areas for respective functions is however limited at present. tDCS is a non-invasive brain stimulation method that alters cortical activity and excitability, and thus might be a useful tool for delineating the specific impact of both areas on word recognition. The objective of this study was to explore whether the visual recognition process of verb categories is improved by a single tDCS session. **Methods:** Broca's and Wernicke's areas, defined as the anatomical regions of the left inferior frontal gyrus (IIFG) and left posterior superior temporal gyrus (lpSTG), respectively, were separately modulated by anodal tDCS (1.5 mA current strength) to evaluate its effects on verbal recognition. **Results:** Compared to sham stimulation, reaction times (RTs) were reduced after lpSTG anodal tDCS, and this effect was independent of the type of verb used in the verbal task (movement, emotional and neutral verbs) and performing hand (right or left). Anodal tDCS over the IIFG reduced RTs only trend-wise. **Conclusions:** These findings suggest that the lpSTG region is involved in word recognition independently from the verb category and performing hand. The contribution of the IIFG to this verbal function is, however, uncertain.

**Keywords:** Anodal direct current stimulation, Broca's area, Reaction time, Verbal recognition, verb category, Wernicke's area

## INTRODUCTION

Visual word recognition is a complex phenomenon that requires the integration of neurocognitive, memory, lexical, orthographic and semantic mechanisms. Different frontal structures and language-related areas provide coordinated mechanisms for this process (Braun et al., 2015). Broca's and Wernicke's areas are two principal cortical regions involved in global language-related functions (Black et al., 2015). Traditionally, Broca's area has been associated with speech production and the motor component of language, and Wernicke's area has been related to speech comprehension and sensory processing of language (Black McL., Black, & Droge, 1986; Chang, Raygor, & Berger, 2015; Iain DeWitt & Rauschecker, 2013; Graves, 1997; Tremblay & Dick, 2016). However, current considerations regarding the architecture of the language system suggest rather a network of connectivity between multiple brain regions in global language processing, in which Broca's (or in a more precise anatomical terminology, the left inferior frontal gyrus -IIFG) and Wernicke's (left posterior superior temporal gyrus -lpSTG) areas are essential nodes (Hagoort, 2014; Price, Crinion, & MacSweeney, 2011). In addition to the traditional language functions outlined above, IIFG and lpSTG have also been shown to be involved in other verbal functions, such as processing and recognition of different verb categories (Iain DeWitt & Rauschecker, 2013; Perry & Lupyan, 2014; Tate, Herbet, Moritz-Gasser, Tate, & Duffau, 2014). Indeed, because of the connections between the IIFG and lpSTG, as well as the fact that auditory recognition of different categories of words (i.e., different verbs or semantics) involves the lpSTG (Iain DeWitt & Rauschecker, 2013) and this region is involved in categorization processes of verbal labels (Perry & Lupyan, 2014), it is likely that the lpSTG is part of the general verbal recognition system. It is however unknown if the

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3 relevance of this region is restricted to specific verb or semantic categories. The region  
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5 of the IIFG has also been associated with higher order language functions. In an event-  
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7 related potential study, patients with a damage of the IIFG failed to perceive past-tense  
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9 for regular, but not for irregular, verbs in a lexical decision task (Justus et al., 2011). A  
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11 specific activity pattern of the IIFG was furthermore revealed by fMRI during  
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13 performance of verbal inflection tasks (Sahin, Pinker, & Halgren, 2006). This indicates  
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15 an involvement of this region in grammatical processing. Besides, a role of the IIFG in  
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17 visual recognition of actions was described (Cerri et al., 2015; Wakita, 2014), which  
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19 might be caused by its proximity to motor areas (Flinker et al., 2015). So far, however, a  
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21 specific role of this region for discriminating verb categories has not been demonstrated.  
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27 Because transcranial magnetic stimulation (TMS) applied over the IIFG region  
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29 (Brückner, Kiefer, & Kammer, 2013; Cappelletti, Fregni, Shapiro, Pascual-Leone, &  
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31 Caramazza, 2008; Shapiro, Pascual-Leone, Mottaghy, Gangitano, & Caramazza, 2001),  
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33 and other brain areas (Argyropoulos, Kimiskidis, & Papagiannopoulos, 2011), is  
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35 effective to modulate verbal functions, other non-invasive brain stimulation (NIBS)  
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37 methods might have similar effects. Transcranial direct current stimulation (tDCS) is a  
38  
39 NIBS tool suited to modulate cortical excitability and activity in humans (Nitsche &  
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41 Paulus, 2000, 2001; Stagg & Nitsche, 2011). With conventional protocols aimed to  
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43 modulate the excitability of motor cortical areas, anodal tDCS (i.e. stimulation with the  
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45 anode positioned over the target area) increases cortical excitability, and cathodal  
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47 stimulation reduces cortical excitability (Agboada et al., 2019; Ghasemian-Shirvan et  
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49 al., 2020; Nitsche & Paulus, 2000, 2001; Nitsche et al., 2003, 2005). However, different  
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51 tDCS protocols have shown that the polarity-dependent effects on motor cortex  
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53 excitability may depend on specific stimulation parameters (Chew, Ho, & Loo, 2015;  
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3 Wiethoff, Hamada, & Rothwell, 2014) and direction of current flow (Faber, Opitz,  
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5 Müller-Dahlhaus, & Ziemann, 2017; Hannah, Iacovou, & Rothwell, 2019; Rawji et al.,  
6  
7 2018). In visual (Antal, Kincses, Nitsche, Bartfai, & Paulus, 2004), somatosensory  
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9 (Matsunaga, Nitsche, Tsuji, & Rothwell, 2004), prefrontal (Filmer, Ehrhardt, Bollmann,  
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11 Mattingley, & Dux, 2019), and temporal areas (Heimrath et al., 2020), such polarity-  
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13 dependent effects on cortical excitability have also been reported, although these might  
14  
15 not be necessarily generalizable to all cortical areas (Jacobson, Koslowsky, & Lavidor,  
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17 2012). From a functional point of view, tDCS might thus have the potential to alter the  
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19 functionality of the language system during verbal task performance as well (Klaus &  
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21 Schutter, 2018a; Richmond, Wolk, Chein, & Olson, 2014), and by these effects reveal  
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23 specific contributions of the respective target areas to task performance. Given the  
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25 polarity-dependent effects of conventional tDCS protocols, anodal stimulation over  
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27 language areas could be considered a means to improve verbal recognition, considering  
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29 that this polarity increases cortical excitability (Heimrath et al., 2020), even though not  
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31 only anodal but also cathodal stimulation over Wernicke's area facilitated word learning  
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33 processes (Blagovechtchenski et al., 2019; Kurmakaeva et al., 2021) and semantic  
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35 processing (Brückner & Kammer, 2017) in some studies. Anodal tDCS also fosters long  
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37 term potentiation (LTP), which is relevant for learning and memory formation (Flöel,  
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39 2012; Ihara et al., 2015; Monti et al., 2013; Pisoni, Vernice, Iasevoli, Cattaneo, &  
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41 Papagno, 2015; Price, McAdams, Grossman, & Hamilton, 2015). However, this does  
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43 not mean that there is a simple connection between physiological and cognitive effects  
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45 of tDCS in each case, in the sense that excitability-enhancing tDCS improves, whereas  
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47 excitability-diminishing tDCS reduces performance. Especially for complex cognitive  
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49 functions, task characteristics are assumed to be relevant for the directionality of  
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51 cognitive effects of tDCS (Jacobson et al., 2012), including language-related processes  
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3 (Sabrina Brückner & Kammer, 2017). In this connection, it has been shown for visuo-  
4 motor coordination that anodal tDCS improved task performance during initial learning  
5 probably via LTP enhancement, whereas cathodal tDCS improved performance in the  
6 overlearned state via enhancement of the signal to noise ratio of cortical activation  
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8 (Antal, Nitsche, Kincses, et al., 2004; Antal, Nitsche, Kruse, et al., 2004).  
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15 Thus, to prove the specific contribution of the IIFG and lpSTG to verbal  
16 recognition processes, we explored the impact of anodal tDCS applied over both regions  
17 on respective task performance in right-handed participants, assuming a left  
18 hemispheric dominance for language representations in this population. Subjects were  
19 instructed to visually discriminate between verb categories, using a previously described  
20 task for recognition of movement-related and -unrelated verbs. The region of the lpSTG  
21 is assumed to be closer related to general word recognition processes than the IIFG,  
22 considering the contribution of the lpSTG to the auditory recognition of different words,  
23 categorized by the phonetic sound, vocalization or meaning (DeWitt & Rauschecker,  
24 2012, 2013). Accordingly, anodal tDCS would induce discernible effects depending on  
25 the visually presented verb category and the respective stimulation target region, with a  
26 non-specific effect on verb recognition in case of modulation of the lpSTG. Stimulation  
27 over the IIFG could induce verb category-dependent effects, most probably on  
28 recognition of movement-related verbs.  
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## 51 **METHOD**

### 52 **Participants**

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3 Forty-eight right-handed (by self-report) healthy volunteers, native Spanish speakers, 24  
4 women and 24 men (mean age  $23.10 \pm 1.90$ ), participated in this study. All of them  
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6 were undergraduate university students in their final year or Master's students. None of  
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8 the participants was under central nervous system-active medication, and none reported  
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10 previous or present neurological or psychiatric disorders. All participants gave written  
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12 informed consent before participation. The experimental procedures were approved by  
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14 the Ethics Committee of the Autonomous University of Baja California and conformed  
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16 to the principles of the World Medical Association Declaration of Helsinki.  
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## 25 **Procedure**

### 26 *Transcranial direct current stimulation (tDCS)*

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31 Anodal and sham tDCS were performed by a battery-driven constant-current stimulator  
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33 (TCT Research Ltd tDCS Stimulator, TST Kowloon, Hong Kong) (Brennan et al.,  
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35 2017; Wexler, 2015) with conductive rubber electrodes placed between two saline-  
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37 soaked sponges. In each session, the target anode electrode was placed over the left  
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39 hemisphere, specifically over the FC5 position (IIFG) or anteriorly to the midpoint  
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41 between CP5 and TP7 (lpSTG), according to the international 10-20 EEG system for  
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43 electrode placement (Herwig, Satrapi, & Schönfeldt-Lecuona, 2003; Klem, Lüders,  
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45 Jasper, & Elger, 1999), based on individual head measures. Stimulation was applied for  
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47 15 min by a  $5 \times 4$  cm ( $20 \text{ cm}^2$ ) saline-soaked sponge electrode at an intensity of 1.5 mA  
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49 ( $0.075 \text{ mA/cm}^2$ ). Similar stimulation protocols result in excitability changes stable for  
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51 about 1 hour after motor cortex tDCS (Nitsche & Paulus, 2000, 2001). A gradual ramp  
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53 up and down of stimulation for 10 sec at the beginning and the end of stimulation,  
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3 respectively, was performed. The cathode return electrode (with a size of 35 cm<sup>2</sup> -7 × 5  
4 cm-, 0.043mA/cm<sup>2</sup>) was placed over the right supraorbital ridge (Fp2 according to the  
5 international 10-20 EEG electrode positioning system). The electrodes were fixed onto  
6 the head by elastic rubber bands. For sham tDCS, current was increased and then  
7 decreased over 10 sec at the beginning and end of the session, respectively, to ensure  
8 some tingling sensation typical for real tDCS, but avoid after-effects of stimulation.  
9 Each subject received direct current stimulation over the IIFG and lpSTG, both anodal  
10 and sham, in randomized order and on separate days at least 1 week apart to avoid  
11 carryover effects. Thus, performance of participants was tested in each of the four  
12 experimental conditions in four separate sessions. After each intervention, participants  
13 were asked about any sensation related to tDCS application during stimulation. Subjects  
14 and the experimenter who recorded and analyzed the data of each session were blinded  
15 to tDCS conditions. SimNIBS 3.1.2 (Simulation of Non-Invasive Brain Stimulation)  
16 was used for modeling the intensity of the electric field induced by the different  
17 electrode configurations. This method has previously been used as computational  
18 modeling software to calculate the intensity of the electric field induced by tDCS  
19 (Saturnino, Siebner, Thielscher, & Madsen, 2019), and analogous modeling methods  
20 have shown to be suited to calculate the specific electric current spread with similar  
21 electrode configurations (Bhattacharjee et al., 2019; Ramaraju, Roula, & McCarthy,  
22 2018).

### 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 *Verbal task*

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56 Subjects performed a verbal task in front of a computer screen located at about 50 cm  
57 eye distance using a keyboard in which two selected keys (one on the right -P key- and  
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3 one on the left -Q key-) served as respond keys. Twenty-four of the subjects were  
4 instructed to press the right key with the right index finger when a movement verb (for  
5 example “bailar” -to dance-, “caminar” -walk-, “escribir” -write-) was displayed on the  
6 center of the computer screen, and the left key with the left index finger when a verb not  
7 related to movement (emotional verbs, like “desear” -to wish-, “dudar” -to doubt-,  
8 “discutir” -argue-, or a neutral verb, such as “llover” -to rain-, “explotar” -exploit-,  
9 “helar” -freeze-) was displayed, according to the method previously described for this  
10 task (González-Nosti, Barbón, Rodríguez-Ferreiro, & Cuetos, 2014). To control for a  
11 possible effect of the response hand, the twenty-four remaining subjects were instructed  
12 to press the left key with the left index finger to respond to movement verbs, and the  
13 right key with the right index finger to respond to any verb not related to movement.  
14 Thus, the response hand for each verb category was the opposite in each group. Subjects  
15 were instructed to press the correct key as fast as possible. Verbs were displayed in  
16 black color on a white background. Reaction time (the time interval between the onset  
17 of the stimulus and the response) for correct responses was analyzed as main outcome  
18 parameter.

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41 One hundred and seventy-six Spanish verbs in the infinitive form were selected  
42 for this task (the complete verb list is shown in Table S1 of the Supplemental material).  
43 Forty-four of them were movement verbs and forty-four were emotional verbs. Eighty-  
44 eight neutral verbs were used in the task as neutral verbs. Emotional and neutral verbs  
45 displayed were not significantly different from movement verbs in lexical frequency,  
46 familiarity or age of acquisition, according to the study of González-Nosti et al. (2014).  
47 Reaction time for movement verbs was compared to that of emotional verbs and control  
48 neutral verbs. All verbs were displayed for a maximum of 3000 ms, if there was no  
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3 response. Once a key was pressed, the verb disappeared and the next one was displayed.  
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5 The inter-stimulus interval was set to 1000 ms. A no-go signal (plus sign, +) was  
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7 displayed at the center of the computer screen during the inter-stimulus interval. All  
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9 verbs were displayed in randomized order to control for possible repetition effects  
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11 (Monsell, 1992). Four different versions of the task, each version with a different order  
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13 of the 176 verbs, were counterbalanced in both groups (right vs. left hand to respond to  
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15 each verb category), one in each of the four counterbalanced stimulation conditions  
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17 (anodal/sham tDCS over the IIFG/lpSTG). The duration of the task did not exceed 9  
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19 min.  
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### 28 *Design*

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30 The study was conducted in a double blinded sham-controlled randomized (response  
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32 hand for each verb category and order of verbs) design. The order of the stimulation  
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34 conditions and the order of the four versions of the task were counterbalanced in the  
35  
36 four experimental sessions. Subjects were seated in a comfortable chair during the  
37  
38 experiment. All subjects received tDCS over the IIFG and lpSTG as described above,  
39  
40 both anodal and sham, leading to four counterbalanced stimulation conditions  
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42 distributed in four separate sessions: B-An (anodal stimulation over the IIFG), B-Sham  
43  
44 (sham stimulation over IIFG), W-An (anodal stimulation over the lpSTG), W-Sham  
45  
46 (sham stimulation over the lpSTG). Participants were blinded for each tDCS condition  
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48 (anodal vs. sham). A person not involved in the remaining parts of the study was  
49  
50 programming the stimulation condition for each subject. The verbal task was performed  
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52 immediately after the application of tDCS, according to previous studies  
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54 (Blagovechtchenski et al., 2019; Cattaneo, Pisoni, & Papagno, 2011; Fertoni,  
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3 Brambilla, Cotelli, & Miniussi, 2014; Fertonani, Rosini, Cotelli, Rossini, & Miniussi,  
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5 2010; Penolazzi, Pastore, & Mondini, 2013; Pereira et al., 2013). During stimulation,  
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7 participants were asked to relax, and no specific task or activity was required. Task  
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9 performance required between 7 min and 9 min. Figure 1 depicts the time sequence of  
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11 the procedure used in this experiment.  
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### 25 **Statistical analyses**

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28 The reaction time (RT) between the stimulus onset and response to each verb was  
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30 recorded and analyzed. We recorded 176 values (corresponding to the response to each  
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32 verb) in each of the 48 participants (resulting in 8448 data points) for each stimulation  
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34 condition (anodal tDCS over lpSTG, anodal tDCS over IIFG, and pooled sham  
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36 condition). Since the mean RT to detect a visual stimulus is approximately 190 ms  
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38 (Miller & Low, 2001; Welford, 1980), all RTs shorter than 200 ms (considering that the  
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40 verbal task involved visual discrimination and motor-execution time) and exceeding 3  
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42 standard deviations of the individual mean of each session were discarded, as well as  
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44 errors. The total percentage of RT discarded data points was 2.3% (0.9% of these -180  
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46 values- due to RTs lower than 200 ms). Statistical analyses were performed for non-  
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48 transformed RT values of 48 participants. A linear mixed-effect model, which better  
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50 accounts for variability than a conventional ANOVA, was conducted to analyze the data  
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52 set. To reduce the high number of initial main factors (performing hand for each verb  
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54 category, stimulation condition, target area, and verb category) and the complexity of  
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3 the design, three stimulation conditions were analyzed in this model: anodal tDCS over  
4 IIFG; anodal tDCS over lpSTG, and sham tDCS with pooled data from both sham tDCS  
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6 electrode positions. The resulting fixed effects and levels included in the linear mixed-  
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8 effect model were: hand (right hand vs. left hand), and stimulation condition (IIFG  
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10 anodal tDCS vs. lpSTG anodal tDCS vs. sham). In addition, in order to explore a  
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12 possible influence of the order of the four task versions and the effect of session order  
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14 (from the first to the fourth) on the results, these factors were initially analyzed as main  
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16 fixed effects in the linear mixed-effect model. Because these task order and session  
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18 order factors showed no significance, the reported analyses refer to hand and  
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20 stimulation condition as fixed effects. Subject was analyzed as random intercept (48  
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22 participants), and verb (1 = movement, 2 = emotional, 3 = neutral) was analyzed as a  
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24 random slope in the by-subject intercept. Considering all these factors, two fixed effects  
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26 and their interactions (hand and stimulation condition) and two random effects (subject  
27  
28 and verb) were analyzed using this model (data of the linear mixed-effect model and  
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30 analysis scripts are available in Table S2 of the Supplemental material). Additional  
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32 LMM analyses conducted to analyze RTs considering stimulation as random factor or  
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34 verb as fixed effect, as well as differences of response errors between sham and anodal  
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36 stimulation in each condition, are also available in the Supplemental material (Table S3  
37  
38 and S4, respectively). The complete dataset and analysis results are available in a public  
39  
40 repository (<https://data.mendeley.com/datasets/7n2mc25mt9/3>). The critical level of  
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42 significance in all tests was set to  $p < 0.05$ . The analyses were carried out using SPSS  
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44 software (IBM SPSS Statistics V25.0).  
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## RESULTS

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3 All participants experienced similar scalp tingling sensations under the electrodes when  
4 they were asked after each tDCS condition, although none of them reported any serious  
5 adverse effects during or after the study. Figure 2 shows the calculated current flow (by  
6 finite element model) for the respective electrode positions. Figure 3 shows the mean  
7 RT for each stimulation condition (lpSTG anodal tDCS, IIFG anodal tDCS, and sham  
8 tDCS with pooled data). The results of the analysis conducted by the linear mixed-effect  
9 model are depicted in Table 1.  
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23 INSERT FIGURE 2 APPROXIMATELY HERE, PLEASE  
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36 Since no significant effect of task version order ( $F(3, 26073) = 0.037, p = 0.847$ ) and  
37 session order ( $F(3, 176.149) = 2.343, p = 0.075$ ) were found, the results of the linear  
38 mixed-effect model refer to the remaining main factors. There was no significant effect  
39 of the main factor hand ( $F(1, 26074) = 0.010, p = 0.919$ ). Instead, this model revealed a  
40 significant effect of the main factor stimulation ( $F(2, 26074) = 27.878, p < 0.001$ ), with  
41 faster RTs after lpSTG anodal tDCS compared to IIFG ( $t(1, 13089) = 8.022, p < 0.001$ )  
42 and sham ( $t(1, 19770) = 5.048, p < 0.001$ ) conditions. The interaction between hand and  
43 stimulation was also significant ( $F(2, 26074) = 3.532, p = 0.029$ ). Post-hoc *t*-tests were  
44 conducted to compare each stimulation condition with each other for each performing  
45 hand. These tests showed faster RTs with the right hand when responding to any verb  
46 category after lpSTG anodal tDCS compared to sham stimulation ( $t(1, 9557) = 5.593, p$   
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3 < 0.001) and IIFG anodal tDCS ( $t(1, 6464) = 7.636, p < 0.001$ ), and faster RTs with the  
4 left hand when responding to any verb category after lpSTG anodal tDCS compared to  
5 IIFG anodal tDCS ( $t(1, 6623) = 3.743, p < 0.001$ ). No other significant effects were  
6 found. Mean RT after IIFG anodal tDCS was lower compared to sham tDCS, but the  
7 linear mixed-effect model revealed only a trend-wise effect of the differences between  
8 these two stimulation conditions ( $891.538 \pm 178.523$  vs.  $964.432 \pm 172.82, p = 0.09$ ).  
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10 No differences of response errors between anodal and sham stimulation were found in  
11 any experimental condition ( $p > 0.05$ ; Table S4).  
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## 26 **DISCUSSION**

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29 In this study we investigated the involvement of the IIFG and lpSTG, considered as the  
30 anatomical regions of the classical Broca's and Wernicke's areas, respectively, in verbal  
31 recognition processes via application of tDCS over these areas. Since anodal tDCS was  
32 assumed to increase cortical excitability, and considering the differential roles of these  
33 regions in language processing, different effects of anodal stimulation over each area  
34 were expected depending on the category of verbs used. The results indicate that after  
35 anodal stimulation over the lpSTG, RTs were significantly reduced (Figure 3). Anodal  
36 tDCS over the IIFG resulted only in trend-wise reduced RT values compared to sham  
37 tDCS. The improvement effect on RT after anodal tDCS over the lpSTG, but not over  
38 the IIFG, was significant when correctly responding with any hand. Significant  
39 differences in RTs between the lpSTG and the IIFG were found when correctly  
40 responding with the left hand, and between the lpSTG and the other two stimulation  
41 conditions (sham and IIFG) when correctly responding with the right hand. Overall,  
42 these findings suggest an improving effect of verum tDCS on word recognition, albeit  
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3 this effect is only significant and valid for both performing hands with anodal tDCS  
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5 applied over the lpSTG.  
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9 The results of this study are consistent with verbal recognition functions  
10 attributed to the lpSTG (Dhond, Marinkovic, Dale, Witzel, & Halgren, 2003; Fuggetta,  
11 Rizzo, Pobric, Lavidor, & Walsh, 2009). The word-content independent contribution of  
12 the lpSTG to verbal recognition is in accordance with previous studies, showing that  
13 single word comprehension and retrieval during a single word language task involve the  
14 activity of the lpSTG (Rivera-Urbina, Joya, Nitsche, & Molero-Chamizo, 2019; Wise et  
15 al., 1991). These results suggest a multimodal function of the lpSTG in word  
16 recognition and memory and might explain thus the differential effects of  
17 neuromodulation found in the present study depending on the targeted stimulation area.  
18 The potential activation of the IIFG by anodal tDCS facilitated verbal recognition  
19 processes only trend-wise, which may indicate that this region is not as critically  
20 involved in general verbal processing as the lpSTG. Several studies suggest some  
21 specific functions of the IIFG in verbal processing (Havas et al., 2015). Particularly,  
22 functional neuroimaging data suggest an involvement of the IIFG in complex semantic  
23 processing (Kotz et al., 2010; Makuuchi, Grodzinsky, Amunts, Santi, & Friederici,  
24 2013; Santi, Friederici, Makuuchi, & Grodzinsky, 2015). However, the results of the  
25 present study do not add evidence for this specific function for the verbal recognition  
26 task applied.  
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50 Some limitations of the study should be considered. In this investigation, only  
51 anodal tDCS was applied. The effects of tDCS over both cortical regions on verbal  
52 recognition should also be evaluated via cathodal stimulation in future studies, in light  
53 of results of tDCS studies on language processing which report an effect of cathodal  
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3 stimulation over Wernicke's area (Blagovechtchenski et al., 2019; Brückner &  
4 Kammer, 2017; Kurmakaeva et al., 2021). Moreover, it is worth highlighting some  
5 anatomical issues. The classical rectangular electrodes are considered to have a limited  
6 focality of effects, compared to ring electrodes montages (Datta et al., 2009). In the  
7 present study, cortical regions surrounding the target areas might also have been altered  
8 due to the electrode size, thus affecting the results, including the primary motor cortex.  
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10 Such a spreading effect of stimulation would be compatible with the more prominent  
11 effect of tDCS over the lpSTG, especially when performing with the right hand. It does  
12 however not fit with the missing effect of tDCS over the IIFG, which is situated in  
13 closer proximity to the motor cortex and has well-defined motor functions in language  
14 processing (Flinker et al., 2015), although no excitability changes of the motor cortex  
15 have been found after the stimulation of an even closer region, the dorsolateral  
16 prefrontal cortex (Boros, Poreisz, Münchau, Paulus, & Nitsche, 2008). Therefore, it is  
17 unlikely that incidental stimulation of the motor cortex hand area, which would have  
18 been stronger for the IIFG electrode position, had a critical impact on the results of the  
19 present study. Moreover, based on the modelling results (Figure 2), the electric field  
20 induced by the tDCS protocol extended to non-target areas, but the strongest electrical  
21 fields were apparently obtained for the intended brain regions (the IIFG, with values  
22 around 0.342 V/m, and the lpSTG region, with values around 0.385 V/m) and the effect  
23 of the intervention was dependent on the stimulation region. This is not well compatible  
24 with a non-specific effect of tDCS, and neither are the facts that no effect of the hand  
25 factor was found and no relevant electric field was induced in the right motor cortex,  
26 according to the modeling results (Figure 2). Future research using verbal tasks that do  
27 not require motor responses may help to distinguish verbal recognition processes from  
28 those of the motor network further. Regarding the stimulation induced under the return  
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3 electrode and its potential influence on the results, current flow simulation revealed  
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5 electric fields with similar strength within both, the regions of interest (lpSTG = 0.385  
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7 vs. IIFG = 0.342 V/m) and the contralateral supraorbital area (lpSTG = ~0.193 vs. IIFG  
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9 = ~0.199) (Figure 2), which hardly can explain a selective improvement effect of  
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11 stimulation over only one of the cortical targets. Moreover, the return electrode was  
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13 positioned over the right frontopolar cortex, in which language functions are not  
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15 presumed to be critical for right-handed subjects. On the other hand, considering that a  
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17 visual verbal task was used, a possible general visual-perceptive effect of stimulation on  
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19 the results might also be principally possible. This also seems to be unlikely since the  
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21 lpSTG is not particularly involved in visual recognition, and there is no reason to think  
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23 that this region is more closely involved in visual processing than the IIFG. Besides, no  
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25 relevant electric fields were induced in principal visual areas, according to the modeling  
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27 results (Figure 2). Future studies should however shed light on this issue by the  
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29 inclusion of specific control conditions to exclude language-independent tDCS effects.  
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31 With respect to possible influences of the return electrode position on the results,  
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33 different electrode montages, for example placing the return electrode over homologous  
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35 contralateral areas, might provide further evidence on the specific involvement of the  
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37 lpSTG and IIFG regions in verb recognition. Extracranial positions could also be  
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39 considered, although this montage alters the electric field orientation in relation to  
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41 neuronal orientation (Arlotti, Rahman, Minhas, & Bikson, 2012; Im, Park, Shim,  
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43 Chang, & Kim, 2012; Shahid, Wen, & Ahfock, 2014), which might not result in optimal  
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45 stimulation. Further electrode configurations aimed to stimulation of the supraorbital  
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47 area as a region of interest when evaluating verb recognition could help to determine if  
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49 incidental stimulation of this area, for example when the return electrode is positioned  
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51 over this region, may influence the results. Alternative protocols have been described to  
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3 reduce the non-focality of conventional tDCS when evaluating language functions.  
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5 Slight variations of the specific electrode placement seem to improve the focality of the  
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7 stimulation and should be taken into account in future studies exploring the effects of  
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9 tDCS on language functions (Klaus & Schutter, 2018b).  
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13 A possible last limitation of this study refers to the verbal task. The same 176  
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15 verbs were displayed in randomized order to control for possible repetition effects in  
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17 each experimental condition. The high number of verbs used, the one-week inter-  
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19 session interval, and the randomized order of stimuli presentation make a putative  
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21 practice effect across sessions reasonably unlikely. Moreover, when the order of the task  
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23 versions was analyzed, no effect of this factor on the results was found, and no  
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25 repetition or practice effect was found when session order was analyzed. Despite this,  
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27 the use of different verbal task versions with different stimuli in future studies would  
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29 help to exclude an order and practice effect more definitely. Besides, the inclusion of  
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31 tasks with the same number of verbs per category (movement vs. emotional and neutral  
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33 verbs) would be useful to avoid possible effects of different frequencies of required  
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35 reactions between verb categories more definitely, although in our study such an effect  
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37 of verb category was absent. In addition, the inclusion of other word categories (such as  
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39 nouns) or sentences when evaluating the effect of tDCS on language functions could  
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41 increase our understanding on the wider involvement of the lpSTG and IIFG in specific  
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43 language processes, as it has been shown for Broca's area and its role in sentence  
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45 comprehension via anodal tDCS (Giustolisi, Vergallito, Cecchetto, Varoli, & Romero  
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47 Lauro, 2018; Lum et al., 2019) or repetitive TMS (rTMS) (Lauro, Reis, Cohen,  
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49 Cecchetto, & Papagno, 2010). Finally, the use of a button box for verbal tasks instead of  
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3 keyboards might be useful for controlling possible computer keyboard interface  
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5 dependent time jitters.  
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## 10 11 **CONCLUSIONS**

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14 The results of this study show that anodal tDCS over the lpSTG facilitates word  
15 recognition. RT for any verb category in the verbal task was reduced after stimulation of  
16 this region. Anodal tDCS over the IIFG only showed a trend-wise facilitation effect of  
17 general verbal recognition. These findings suggest that the impact of these regions on  
18 verbal processing differs relevantly. This should be explored in larger detail in future  
19 studies, ideally by combining brain stimulation with physiological monitoring,  
20 including EEG recording, monitoring of event-related spectral perturbations (ERSP),  
21 event-related potentials (ERP) or functional magnetic resonance imaging. In general,  
22 these findings contribute to our understanding of the complex contribution of the  
23 anatomical regions corresponding to the classical Broca's and Wernicke's areas in  
24 verbal recognition processes and might also help to clarify the behavioral effects of non-  
25 invasive brain stimulation applied over essential areas of the language system.  
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**FIGURE CAPTIONS**

**Figure 1. Course of the Experiment.** Transcranial direct current stimulation (tDCS) was applied for 15 minutes at an intensity of 1.5 mA in counterbalanced order in the following four different sessions: anodal vs. sham Broca's area (IIFG) stimulation, and anodal vs. sham Wernicke's area (IpSTG) stimulation. Immediately after stimulation, a verbal categorization task was performed. (a) Right-hand group: subjects were instructed to press with the right index finger the P key of the keyboard when movement verbs were displayed, and with the left index finger the Q key when verbs not related to movement were displayed. (b) Left-hand group: this group followed the opposite procedure, that is, subjects pressed with the right index finger the P key of the keyboard when verbs not-related to movement were displayed, and with the left index finger the Q key when movement verbs were displayed. Maximum duration of the verbal task was 9 min. A different version of the task was performed by each subject in each experimental session, in a counterbalanced order.

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3 **Figure 2. Electric field intensities calculated by finite element modeling according**  
4 **to the tDCS electrode configuration used in this study.** Anodal electrode positions  
5 (black squares) according to the international 10-20 EEG system are shown in the left  
6 superior (lpSTG) and inferior (IIFG) images. In both cases, the cathodal electrode was  
7 positioned over the contralateral supraorbital region (Fp2). SimNIBS 3.1.2 (Simulation  
8 of Non-Invasive Brain Stimulation) free software was used for modeling of the electric  
9 field. Superior and inferior SimNIBS output brain images show a lateral, dorsal and  
10 frontal view of the current flow induced by tDCS over the lpSTG and IIFG,  
11 respectively. The electric field (normE) intensity (V/m) is represented by the color bar  
12 (online version). The brighter colors (higher numbers depicted in the color bar) indicate  
13 higher electric field intensity (0.385 V/m at the lpSTG, and 0.342 V/m at the IIFG). Red  
14 and blue electrodes of the SimNIBS output brain images represent the anodal and  
15 cathodal electrode position, respectively.  
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3 **Figure 3. Reaction time (RT) in the verbal recognition task.** A linear mixed-effect  
4 model revealed reduced RTs after anodal stimulation over Wernicke's area (lpSTG),  
5 compared to pooled data from sham tDCS over the lpSTG and Broca's area (IIFG) ( $*p$   
6  $< 0.001$ ). Anodal tDCS over the IIFG reduced RT values only trend-wise. An  
7 interaction between stimulation condition and performing hand was found ( $p < 0.001$ ).  
8 Anodal tDCS over the lpSTG, but not over the IIFG, significantly reduced RT when the  
9 task was performed with the right or left hand, as compared to IIFG stimulation ( $p <$   
10  $0.001$ , in both cases), and additionally lpSTG stimulation reduced RT compared to sham  
11 stimulation when task was performed with the right hand ( $p < 0.001$ ). Error bars  
12 represent standard error of means (SEM).  
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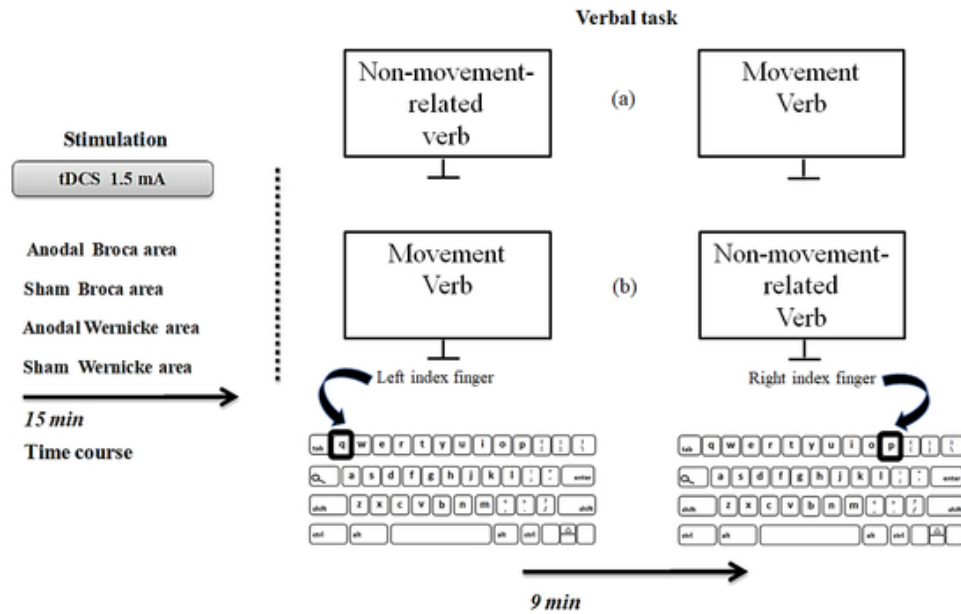


Figure 1. Course of the Experiment. Transcranial direct current stimulation (tDCS) was applied for 15 minutes at an intensity of 1.5 mA in counterbalanced order in the following four different sessions: anodal vs. sham Broca's area (IFG) stimulation, and anodal vs. sham Wernicke's area (IpSTG) stimulation. Immediately after stimulation, a verbal categorization task was performed. (a) Right-hand group: subjects were instructed to press with the right index finger the P key of the keyboard when movement verbs were displayed, and with the left index finger the Q key when verbs not related to movement were displayed. (b) Left-hand group: this group followed the opposite procedure, that is, subjects pressed with the right index finger the P key of the keyboard when verbs not-related to movement were displayed, and with the left index finger the Q key when movement verbs were displayed. Maximum duration of the verbal task was 9 min. A different version of the task was performed by each subject in each experimental session, in a counterbalanced order.

48x30mm (300 x 300 DPI)

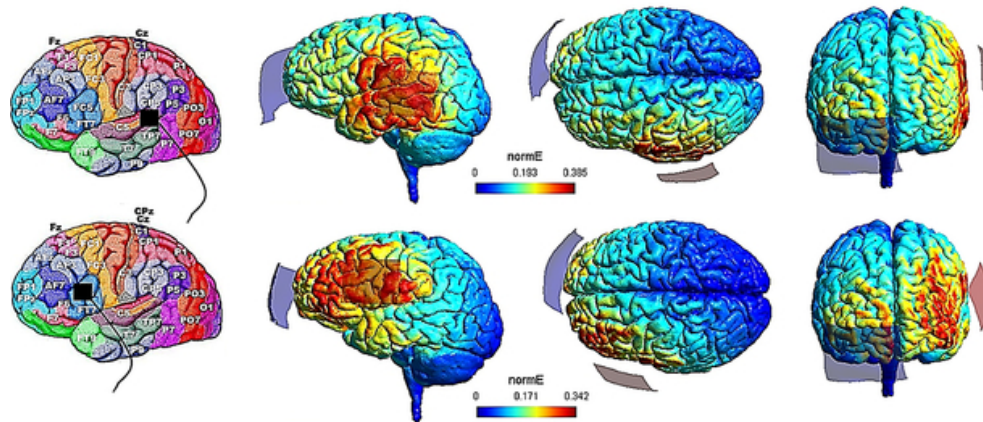


Figure 2. Electric field intensities calculated by finite element modeling according to the tDCS electrode configuration used in this study. Anodal electrode positions (black squares) according to the international 10-20 EEG system are shown in the left superior (IpSTG) and inferior (IFG) images. In both cases, the cathodal electrode was positioned over the contralateral supraorbital region (Fp2). SimNIBS 3.1.2 (Simulation of Non-Invasive Brain Stimulation) free software was used for modeling of the electric field. Superior and inferior SimNIBS output brain images show a lateral, dorsal and frontal view of the current flow induced by tDCS over the IpSTG and IFG, respectively. The electric field (normE) intensity (V/m) is represented by the color bar (online version). The brighter colors (higher numbers depicted in the color bar) indicate higher electric field intensity (0.385 V/m at the IpSTG, and 0.342 V/m at the IFG). Red and blue electrodes of the SimNIBS output brain images represent the anodal and cathodal electrode position, respectively.

52x22mm (300 x 300 DPI)

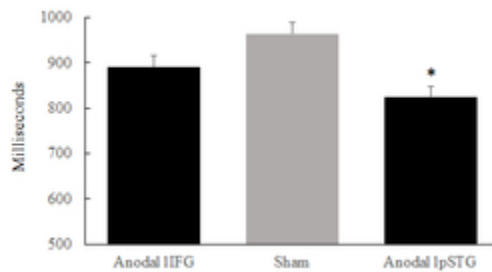


Figure 3. Reaction time (RT) in the verbal recognition task. A linear mixed-effect model revealed reduced RTs after anodal stimulation over Wernicke's area (IpSTG), compared to pooled data from sham tDCS over the IpSTG and Broca's area (IIFG) (\* $p < 0.001$ ). Anodal tDCS over the IIFG reduced RT values only trend-wise. An interaction between stimulation condition and performing hand was found ( $p < 0.001$ ). Anodal tDCS over the IpSTG, but not over the IIFG, significantly reduced RT when the task was performed with the right or left hand, as compared to IIFG stimulation ( $p < 0.001$ , in both cases), and additionally IpSTG stimulation reduced RT compared to sham stimulation when task was performed with the right hand ( $p < 0.001$ ). Error bars represent standard error of means (SEM).

22x12mm (300 x 300 DPI)

**Table 1**

Results of the linear mixed-effect model.

	<b>N.d.f.</b>	<b>F-value</b>	<b>p-value</b>	
<b>Estimates of fixed effects</b>				
Intercept	1	32.631	< 0.001*	
Hand	1	0.010	0.227	
Stimulation	2	27.878	< 0.001*	
Hand × Stimulation	2	3.532	< 0.001*	
<b>Random effects</b>				
<b>Estimates with 95% credibility limits</b>				
<b>Factor</b>	<b>Error deviation</b>	<b>p-value</b>	<b>Lower</b>	<b>Upper</b>
S1 Verb 1	29.456	0.003	-144.977	-29.353
S1 Verb 2	28.276	> 0.05	-251.232	-140.217
S1 Verb 3	25.341	0.002	-129.217	-29.651
S2 Verb 1	30.350	> 0.05	87.922	207.039
S2 Verb 2	29.586	> 0.05	59.965	176.098
S2 Verb 3	25.899	> 0.05	93.393	195.136
S3 Verb 1	31.666	< 0.001	-397.497	-273.237
S3 Verb 2	30.422	< 0.001	-413.606	-294.209
S3 Verb 3	26.042	< 0.001	-401.227	-298.928
S4 Verb 1	29.270	> 0.05	81.337	196.234
S4 Verb 2	28.080	> 0.05	-47.433	62.816
S4 Verb 3	26.792	> 0.05	150.120	255.342
S5 Verb 1	29.520	> 0.05	-78.275	37.598
S5 Verb 2	27.846	> 0.05	-194.805	-85.470
S5 Verb 3	25.868	0.036	-105.104	-3.484
S6 Verb 1	29.521	0.288	-89.314	26.562
S6 Verb 2	27.985	0.099	-101.204	8.674
S6 Verb 3	26.038	0.367	-27.620	74.666
S7 Verb 1	29.032	0.245	-23.213	90.753
S7 Verb 2	29.270	0.434	-34.545	80.352
S7 Verb 3	25.809	0.002	30.675	132.066
S8 Verb 1	28.533	0.548	-73.143	38.875
S8 Verb 2	29.270	0.941	-59.603	55.294
S8 Verb 3	24.669	0.364	-26.080	70.871
S9 Verb 1	28.377	0.018	-123.260	-11.850

1					
2	S9 Verb 2	27.892	> 0.05	-191.205	-81.692
3	S9 Verb 3	24.454	0.609	-60.565	35.549
4					
5	S10 Verb 1	27.938	> 0.05	-246.524	-136.830
6	S10 Verb 2	28.128	> 0.05	-185.609	-75.171
7	S10 Verb 3	23.755	> 0.05	-179.965	-86.569
8					
9					
10	S11 Verb 1	30.494	0.001	40.012	159.691
11	S11 Verb 2	29.650	0.967	-59.423	56.958
12	S11 Verb 3	26.519	0.004	24.207	128.367
13					
14	S12 Verb 1	32.341	> 0.05	178.649	305.548
15	S12 Verb 2	29.032	> 0.05	146.455	260.422
16	S12 Verb 3	28.379	< 0.001	217.006	328.424
17					
18					
19	S13 Verb 1	29.850	< 0.001	53.924	171.087
20	S13 Verb 2	28.032	0.689	-43.826	66.236
21	S13 Verb 3	27.851	> 0.05	125.517	234.874
22					
23	S14 Verb 1	35.051	0.116	-13.704	123.803
24	S14 Verb 2	28.226	0.001	35.382	146.202
25	S14 Verb 3	27.635	0.967	-53.102	55.410
26					
27					
28	S15 Verb 1	29.271	0.222	-21.676	93.225
29	S15 Verb 2	28.430	0.005	24.427	136.040
30	S15 Verb 3	26.555	> 0.05	116.873	221.171
31					
32	S16 Verb 1	28.128	0.955	-56.821	53.616
33	S16 Verb 2	29.210	0.388	-82.567	32.094
34	S16 Verb 3	24.530	0.898	-51.358	45.052
35					
36					
37	S17 Verb 1	29.781	> 0.05	-204.681	-87.788
38	S17 Verb 2	27.846	> 0.05	-242.877	-133.543
39	S17 Verb 3	24.710	> 0.05	-225.955	-128.844
40					
41	S18 Verb 1	30.421	0.434	-35.863	83.529
42	S18 Verb 2	28.481	0.642	-42.648	69.167
43	S18 Verb 3	26.422	0.183	-87.151	16.627
44					
45					
46	S19 Verb 1	29.459	> 0.05	137.533	253.166
47	S19 Verb 2	28.534	< 0.001	55.164	167.186
48	S19 Verb 3	26.760	< 0.001	202.331	307.431
49					
50					
51	S20 Verb 1	28.129	0.473	-75.434	35.004
52	S20 Verb 2	29.271	0.043	1.751	116.652
53	S20 Verb 3	24.255	0.207	-16.987	78.354
54					
55	S21 Verb 1	29.090	0.006	23.767	137.961
56	S21 Verb 2	28.378	0.629	-41.999	69.413
57	S21 Verb 3	25.807	0.002	28.428	129.810
58					
59					
60	S22 Verb 1	29.150	0.026	7.993	122.422

1					
2	S22 Verb 2	28.750	0.198	-93.491	19.373
3	S22 Verb 3	25.192	< 0.001	47.078	146.066
4					
5	S23 Verb 1	29.094	< 0.001	-430.552	-316.342
6	S23 Verb 2	28.589	< 0.001	-370.543	-258.308
7	S23 Verb 3	24.293	< 0.001	-428.549	-333.059
8					
9	S24 Verb 1	31.755	> 0.05	171.230	295.841
10	S24 Verb 2	28.805	0.947	-54.641	58.437
11	S24 Verb 3	28.178	< 0.001	201.630	312.262
12					
13					
14	S25 Verb 1	28.580	0.023	9.214	121.414
15	S25 Verb 2	28.270	0.276	-24.653	86.336
16	S25 Verb 3	24.246	0.006	18.985	114.291
17					
18					
19	S26 Verb 1	28.423	> 0.05	120.951	232.538
20	S26 Verb 2	27.931	0.054	-1.028	108.641
21	S26 Verb 3	24.684	> 0.05	146.121	243.131
22					
23	S27 Verb 1	28.171	> 0.05	-294.344	-183.741
24	S27 Verb 2	27.932	> 0.05	-248.142	-138.473
25	S27 Verb 3	23.689	< 0.001	-307.804	-214.665
26					
27					
28	S28 Verb 1	27.793	0.911	-57.676	51.454
29	S28 Verb 2	28.026	0.495	-74.159	35.878
30	S28 Verb 3	24.092	0.163	-13.676	81.032
31					
32	S29 Verb 1	27.839	> 0.05	-256.270	-146.962
33	S29 Verb 2	27.839	> 0.05	-251.528	-142.748
34	S29 Verb 3	23.703	> 0.05	-232.199	-139.004
35					
36					
37	S30 Verb 1	28.073	0.013	-125.368	-15.145
38	S30 Verb 2	27.704	< 0.001	-155.508	-46.728
39	S30 Verb 3	24.143	0.004	-117.147	-22.243
40					
41					
42	S31 Verb 1	28.968	> 0.05	186.661	300.376
43	S31 Verb 2	28.527	0.015	13.423	125.416
44	S31 Verb 3	24.911	> 0.05	144.141	242.035
45					
46	S32 Verb 1	30.801	0.077	-5.896	114.983
47	S32 Verb 2	28.422	0.384	-80.545	31.040
48	S32 Verb 3	26.278	0.871	-55.888	47.333
49					
50					
51	S33 Verb 1	29.388	> 0.05	-295.037	-179.681
52	S33 Verb 2	29.387	> 0.05	-270.671	-155.318
53	S33 Verb 3	24.890	> 0.05	-238.179	-140.369
54					
55	S34 Verb 1	28.371	0.005	-134.688	-23.302
56	S34 Verb 2	28.026	0.001	-150.595	-40.559
57	S34 Verb 3	24.505	0.204	-79.312	17.002
58					
59					
60	S35 Verb 1	29.911	< 0.001	206.835	324.235

1					
2	S35 Verb 2	29.387	0.001	43.447	158.800
3	S35 Verb 3	27.009	< 0.001	223.399	329.469
4					
5	S36 Verb 1	28.321	< 0.001	-157.352	-46.164
6	S36 Verb 2	29.453	0.155	-15.880	99.732
7	S36 Verb 3	28.088	0.811	-48.405	61.876
8					
9	S37 Verb 1	28.026	> 0.05	-260.478	-150.441
10	S37 Verb 2	28.854	> 0.05	-256.639	-143.368
11	S37 Verb 3	23.837	> 0.05	-230.951	-137.235
12					
13					
14	S38 Verb 1	28.798	0.106	-9.961	103.092
15	S38 Verb 2	28.122	0.946	-53.295	57.118
16	S38 Verb 3	24.762	0.093	-7.032	90.283
17					
18					
19	S39 Verb 1	31.213	> 0.05	66.105	188.596
20	S39 Verb 2	28.855	0.067	-3.715	109.558
21	S39 Verb 3	28.531	< 0.001	47.979	159.989
22					
23	S40 Verb 1	28.073	> 0.05	-254.151	-143.928
24	S40 Verb 2	28.074	< 0.001	-305.796	-195.573
25	S40 Verb 3	24.282	> 0.05	-197.354	-101.909
26					
27					
28	S41 Verb 1	28.320	0.974	-56.525	54.660
29	S41 Verb 2	28.634	> 0.05	173.249	285.661
30	S41 Verb 3	25.857	> 0.05	121.721	223.300
31					
32	S42 Verb 1	28.633	0.044	-114.038	-1.628
33	S42 Verb 2	28.171	0.151	-95.795	14.807
34	S42 Verb 3	24.805	0.208	-17.448	80.033
35					
36					
37	S43 Verb 1	34.200	> 0.05	150.497	284.670
38	S43 Verb 2	28.911	< 0.001	55.972	169.468
39	S43 Verb 3	29.915	> 0.05	105.399	222.816
40					
41					
42	S44 Verb 1	30.339	< 0.001	217.236	336.307
43	S44 Verb 2	28.742	> 0.05	62.809	175.644
44	S44 Verb 3	26.407	< 0.001	232.241	335.964
45					
46	S45 Verb 1	29.084	0.260	-89.897	24.274
47	S45 Verb 2	27.931	< 0.001	-158.173	-48.504
48	S45 Verb 3	25.505	0.005	-122.261	-22.055
49					
50					
51	S46 Verb 1	29.203	> 0.05	90.828	205.463
52	S46 Verb 2	27.885	0.015	13.154	122.642
53	S46 Verb 3	26.309	> 0.05	150.521	253.861
54					
55	S47 Verb 1	28.800	0.142	-14.231	98.827
56	S47 Verb 2	29.775	0.863	-63.579	53.291
57	S47 Verb 3	24.889	0.015	11.932	109.741
58					
59					
60	S48 Verb 1	29.026	0.004	-140.321	-26.378

S48 Verb 2	27.931	> 0.05	-223.803	-114.134
S48 Verb 3	25.428	> 0.05	-156.080	-56.175

*Note.* A linear mixed-effect model (LMM) (with the fixed factors hand and stimulation condition) was calculated by the restricted maximum likelihood (REML) method for non-transformed values of 48 participants. Subject ( $n = 48$ ) was analyzed as random intercept, and verb (1 = movement, 2 = emotional, 3 = neutral) was analyzed as a random slope in the by-subject intercept. For this model, data from both sham tDCS positions (lpSTG and IIFG) were pooled, resulting in three stimulation conditions: lpSTG anodal tDCS, IIFG anodal tDCS, Sham tDCS.  $*p < 0.05$ . N.d.f., degrees of freedom of the numerator. S, subject. Degrees of freedom of the denominator for fixed factors = 26074.

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2  
3 **Effects of tDCS applied over Broca's and Wernicke's areas on verbal recognition**  
4  
5 **task performance**  
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7

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**CONTENTS**

List of verbs used in the verbal task: Table S1

Results of the linear mixed-effect model (LMM): Table S2

Stimulation effect as random factor in the LMM: Table S3

Response errors for sham and anodal stimulation in each condition: Table S4

**Table S1****LIST OF SPANISH VERBS USED IN THE VERBAL TASK**

MOVEMENT	EMOTIONAL	FILLER	
12	acariciar	acertar	acontecer gratinar
13	acarrear	afrontar	amanecer graznar
14	afeitar	animar	anocheecer hervir
15	aplaudir	apoyar	arriar hibernar
16	anotar	asumir	atardecer helar
17	articular	ayudar	aterrizar iluminar
18	bailar	causar	aullar voznar
19	batir	conocer	balar churritar
20	cazar	creer	barritar inundar
21	caminar	dedicar	bramar ladrar
22	construir	defender	brillar latir
23	correr	desear	brotar llover
24	cortar	discutir	bufar lloviznar
25	coser	dudar	cacarear marchitar
26	deambular	educar	burbujear maullar
27	disparar	envidiar	centrifugar mugir
28	enterrar	estremecer	chirriar nevar
29	escapar	extrañar	cloquear nublar
30	escribir	fallar	coagular ocurrir
31	fabricar	fingir	cocear oscurecer
32	firmar	gustar	olear pastar
33	fregar	herir	croar piar
34	huir	imaginar	crujir trisar
35	imitar	intuir	derretir podrir
36	lanzar	inventar	desbordar polinizar
37	montar	llorar	descarrilar rebuznar
38	morder	lograr	diluviar reflejar
39	mover	mentir	ondear anegar
40	narrar	necesitar	eclosionar regurgitar
41	nadar	negar	erosionar relampaguear
42	operar	obedecer	escampar relinchar
43	orinar	odiar	oxidar ronronear
44	pasear	pensar	estallar rugir
45	pegar	querer	evaporar rumiar
46	pestañear	rechazar	explotar suceder
47	planchar	recordar	fermentar transcurrir
48	sacar	saber	floreecer trinar

1				
2				
3	saltar	sentir	fluir	gañir
4	subir	soñar	fotocopiar	tronar
5	tejer	sospechar	galopar	ulular
6	tirar	suspender	gorjear	vibrar
7	traer	temer	gotear	lixiviar
8	trazar	valer	grajear	zarpar
9	trazar	valer	grajear	zarpar
10	trazar	valer	grajear	zarpar
11	trazar	valer	grajear	zarpar
12	trazar	valer	grajear	zarpar
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3 **LIST OF VERBS USED IN THE VERBAL TASK**  
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5 **(English translation)**  
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9 *Note:* this is a free translation of the standardized task with Spanish verbs described in the  
10 article of González-Nosti (González-Nosti, M., Barbón, A., Rodríguez-Ferreiro, J., &  
11 Cuetos, F. (2013). Effects of the psycholinguistic variables on the lexical decision task in  
12 Spanish: A study with 2,765 words. *Behavior Research Methods*, 46, 517-525.  
13 <http://dx.doi.org/10.3758/s13428-013-0383-5>), and therefore it should not be considered  
14 a precise translation to be used as a standardized task in English. There are Spanish verbs  
15 with difficult or unrealistic translation to another languages, including English. This  
16 translation has the sole purpose of providing guidance on the kind of verbs used in the  
17 above-mentioned standardized task.  
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## MOVEMENT

to caress  
carry  
to shave  
applaud  
annotate  
articulate  
dance  
shake  
hunt  
walk  
build  
run  
cut  
sew  
wander  
shoot  
bury  
escape  
to write  
manufacture  
sign  
scrub  
run away  
imitate  
throw  
mount  
to bite  
move  
narrate  
swim  
operate  
to pee  
take a walk  
paste  
blink  
iron  
extract  
jump  
go up  
to knit  
throw  
bring  
draw  
climb

## EMOTIONAL

guess  
front facing  
encourage  
support  
assume  
to help  
to cause  
know  
believe  
to dedicate  
defend  
to wish  
discuss  
doubt  
educate  
to envy  
shake  
miss  
fail  
pretend  
like  
hurt  
to imagine  
to sense  
invent  
cry  
achieve  
to lie  
need  
deny  
obey  
to hate  
think  
want  
to refuse  
to remember  
to know  
to feel  
to dream  
suspect  
suspend  
to fear  
to worth  
assess

## FILLER

happen  
Sunrise  
darkle  
haul down  
get dark  
to land  
to howl  
to bleat  
trumpet  
roar  
shine  
to sprout  
snort  
to cackle  
bubble up  
spin-dry  
squeak  
to cluck  
coagulate  
to kick  
flutter  
croak  
creak  
melt  
overflow  
derail  
deluge  
wave  
hatch  
erode  
scatter  
oxidize  
burst  
evaporate  
exploit  
ferment  
to flourish  
flow  
photocopy  
gallop  
warble  
Drip  
graze  
hail

gratin  
squawk  
boil  
hibernate  
freeze  
to illuminate  
voice  
churritar  
flood  
to bark  
beat  
to rain  
drizzle  
wither  
meow  
moo  
to snow  
cloud  
occur  
darken  
pasture  
tweet  
trisar  
rot  
pollinate  
bray  
reflect  
flood  
regurgitate  
flash  
neigh  
purr  
roar  
ruminate  
happen  
elapse  
trill  
yelp  
thunder  
hoot  
vibrate  
leach out  
set sail  
buzz

**Table S2**

**Results of the linear mixed-effect model (LMM) with the fixed factors Hand and Stimulation condition, and with Subject ( $n = 48$ ) as random intercept, and verb as a random slope in the by-subject intercept.**

**ANALYSIS SCRIPTS OF THE LINEAR MIXED-EFFECT MODEL**

MIXED Time BY Hand Stimulation Verb

/CRITERIA=CIN(95) MXITER(100) MXSTEP(10) SCORING(1) SINGULAR(0.000000000001)  
HCONVERGE(0,

ABSOLUTE) LCONVERGE(0, ABSOLUTE) PCONVERGE(0.000001, ABSOLUTE)

/FIXED=Hand Stimulation Hand\*Stimulation | SSTYPE(3)

/METHOD=REML

/PRINT=DESCRIPTIVES G SOLUTION

/RANDOM=Verb | SUBJECT(Sujeto) COVTYPE(VC)

/EMMEANS=TABLES(Hand) COMPARE ADJ(BONFERRONI)

/EMMEANS=TABLES(Stimulation) COMPARE ADJ(BONFERRONI)

/EMMEANS=TABLES(Hand\*Stimulation).

LMM							
Subject	Parameter (factor)	Prediction	Error deviation	Degrees of freedom	Sig.	95% confidence interval	
						Lower limit	Upper limit
1	[Verb=1]	-87.165	29.456	890.283	.003	-144.977	-29.353
	[Verb=2]	-195.725	28.276	771.742	9.380E-12	-251.232	-
	[Verb=3]	-79.434	25.341	517.036	.002	-129.217	140.217
2	[Verb=1]	147.481	30.350	985.543	1.370E-6	87.922	207.039
	[Verb=2]	118.032	29.586	903.866	7.161E-5	59.965	176.098
	[Verb=3]	144.265	25.899	560.868	3.952E-8	93.393	195.136
3	[Verb=1]	-335.367	31.666	1133.237	.000	-397.497	-
	[Verb=2]	-353.908	30.422	993.362	.000	-413.606	273.237
	[Verb=3]	-350.077	26.042	572.427	.000	-401.227	-
4	[Verb=1]	138.785	29.270	871.003	2.477E-6	81.337	196.234
	[Verb=2]	7.691	28.080	752.885	.784	-47.433	62.816
	[Verb=3]	202.731	26.792	635.464	1.348E-13	150.120	255.342
5	[Verb=1]	-20.339	29.520	896.919	.491	-78.275	37.598
	[Verb=2]	-140.137	27.846	730.708	6.097E-7	-194.805	-85.470
	[Verb=3]	-54.294	25.868	558.327	.036	-105.104	-3.484
6	[Verb=1]	-31.376	29.521	897.007	.288	-89.314	26.562
	[Verb=2]	-46.265	27.985	743.827	.099	-101.204	8.674
	[Verb=3]	23.523	26.038	572.141	.367	-27.620	74.666
7	[Verb=1]	33.770	29.032	846.659	.245	-23.213	90.753
	[Verb=2]	22.903	29.270	871.006	.434	-34.545	80.352
	[Verb=3]	81.371	25.809	553.639	.002	30.675	132.066
8	[Verb=1]	-17.134	28.533	796.807	.548	-73.143	38.875
	[Verb=2]	-2.155	29.270	871.039	.941	-59.603	55.294
	[Verb=3]	22.396	24.669	467.239	.364	-26.080	70.871
9	[Verb=1]	-67.555	28.377	781.559	.018	-123.260	-11.850
	[Verb=2]	-136.449	27.892	735.007	1.226E-6	-191.205	-81.692
	[Verb=3]	-12.508	24.454	451.999	.609	-60.565	35.549
10	[Verb=1]	-191.677	27.938	739.385	1.448E-11	-246.524	-
	[Verb=2]	-130.390	28.128	757.501	4.192E-6	-185.609	136.830
	[Verb=3]	-133.267	23.755	404.648	3.754E-8	-179.965	-75.171
11	[Verb=1]	99.852	30.494	1001.264	.001	40.012	159.691
	[Verb=2]	-1.233	29.650	910.534	.967	-59.423	56.958
	[Verb=3]	76.287	26.519	612.110	.004	24.207	128.367
12	[Verb=1]	242.099	32.341	1211.925	1.363E-13	178.649	305.548
	[Verb=2]	203.438	29.032	846.671	4.956E-12	146.455	260.422
	[Verb=3]	272.715	28.379	781.751	.000	217.006	328.424
13	[Verb=1]	112.505	29.850	931.699	.000	53.924	171.087
	[Verb=2]	11.205	28.032	748.331	.689	-43.826	66.236
	[Verb=3]	180.196	27.851	731.236	1.795E-10	125.517	234.874

1								
2								
3								
4	14	[Verb=1]	55.050	35.051	1540.831	.116	-13.704	123.803
5		[Verb=2]	90.792	28.226	766.934	.001	35.382	146.202
6		[Verb=3]	1.154	27.635	711.052	.967	-53.102	55.410
7	15	[Verb=1]	35.775	29.271	871.102	.222	-21.676	93.225
8		[Verb=2]	80.234	28.430	786.645	.005	24.427	136.040
9		[Verb=3]	169.022	26.555	615.123	3.818E-10	116.873	221.171
10	16	[Verb=1]	-1.602	28.128	757.496	.955	-56.821	53.616
11		[Verb=2]	-25.237	29.210	864.792	.388	-82.567	32.094
12		[Verb=3]	-3.153	24.530	457.343	.898	-51.358	45.052
13	17	[Verb=1]	-146.234	29.781	924.384	1.075E-6	-204.681	-87.788
14		[Verb=2]	-188.210	27.846	730.699	2.842E-11	-242.877	-
15		[Verb=3]	-177.400	24.710	470.198	2.753E-12	-225.955	133.543
16								-
17								128.844
18	18	[Verb=1]	23.833	30.421	993.229	.434	-35.863	83.529
19		[Verb=2]	13.259	28.481	791.694	.642	-42.648	69.167
20		[Verb=3]	-35.262	26.422	603.854	.183	-87.151	16.627
21	19	[Verb=1]	195.349	29.459	890.528	5.765E-11	137.533	253.166
22		[Verb=2]	111.175	28.534	796.912	.000	55.164	167.186
23		[Verb=3]	254.881	26.760	632.775	.000	202.331	307.431
24	20	[Verb=1]	-20.215	28.129	757.524	.473	-75.434	35.004
25		[Verb=2]	59.201	29.271	871.117	.043	1.751	116.652
26		[Verb=3]	30.684	24.255	438.174	.207	-16.987	78.354
27	21	[Verb=1]	80.864	29.090	852.599	.006	23.767	137.961
28		[Verb=2]	13.707	28.378	781.610	.629	-41.999	69.413
29		[Verb=3]	79.119	25.807	553.450	.002	28.428	129.810
30	22	[Verb=1]	65.208	29.150	858.732	.026	7.993	122.422
31		[Verb=2]	-37.059	28.750	818.271	.198	-93.491	19.373
32		[Verb=3]	96.572	25.192	505.746	.000	47.078	146.066
33	23	[Verb=1]	-373.447	29.094	852.994	.000	-430.552	-
34								316.342
35		[Verb=2]	-314.426	28.589	802.267	.000	-370.543	-
36								258.308
37		[Verb=3]	-380.804	24.293	440.819	.000	-428.549	-
38								333.059
39	24	[Verb=1]	233.535	31.755	1143.592	3.653E-13	171.230	295.841
40		[Verb=2]	1.898	28.805	823.737	.947	-54.641	58.437
41		[Verb=3]	256.946	28.178	762.275	.000	201.630	312.262
42	25	[Verb=1]	65.314	28.580	801.400	.023	9.214	121.414
43		[Verb=2]	30.842	28.270	771.106	.276	-24.653	86.336
44		[Verb=3]	66.638	24.246	437.572	.006	18.985	114.291
45	26	[Verb=1]	176.744	28.423	785.999	8.153E-10	120.951	232.538
46		[Verb=2]	53.806	27.931	738.769	.054	-1.028	108.641
47		[Verb=3]	194.626	24.684	468.331	2.240E-14	146.121	243.131
48	27	[Verb=1]	-239.043	28.171	761.564	2.000E-16	-294.344	-
49								183.741
50		[Verb=2]	-193.308	27.932	738.787	9.755E-12	-248.142	-
51								138.473
52		[Verb=3]	-261.234	23.689	400.346	.000	-307.804	-
53								214.665
54	28	[Verb=1]	-3.111	27.793	725.802	.911	-57.676	51.454
55		[Verb=2]	-19.140	28.026	747.710	.495	-74.159	35.878
56		[Verb=3]	33.678	24.092	427.079	.163	-13.676	81.032
57	29	[Verb=1]	-201.616	27.839	730.070	1.123E-12	-256.270	-
58								146.962
59								
60								

	[Verb=2]	-197.138	27.704	717.432	2.699E-12	-251.528	-
							142.748
	[Verb=3]	-185.602	23.703	401.284	4.370E-14	-232.199	-
							139.004
30	[Verb=1]	-70.256	28.073	752.253	.013	-125.368	-15.145
	[Verb=2]	-101.118	27.704	717.436	.000	-155.508	-46.728
	[Verb=3]	-69.695	24.143	430.499	.004	-117.147	-22.243
31	[Verb=1]	243.518	28.968	840.154	2.000E-16	186.661	300.376
	[Verb=2]	69.420	28.527	796.180	.015	13.423	125.416
	[Verb=3]	193.088	24.911	484.846	5.400E-14	144.141	242.035
32	[Verb=1]	54.544	30.801	1035.219	.077	-5.896	114.983
	[Verb=2]	-24.752	28.422	785.950	.384	-80.545	31.040
	[Verb=3]	-4.277	26.278	591.889	.871	-55.888	47.333
33	[Verb=1]	-237.359	29.388	883.160	2.200E-15	-295.037	-
							179.681
	[Verb=2]	-212.994	29.387	883.086	9.237E-13	-270.671	-
							155.318
	[Verb=3]	-189.274	24.890	483.267	1.503E-13	-238.179	-
							140.369
34	[Verb=1]	-78.995	28.371	780.963	.005	-134.688	-23.302
	[Verb=2]	-95.577	28.026	747.698	.001	-150.595	-40.559
	[Verb=3]	-31.155	24.505	455.609	.204	-79.312	17.002
35	[Verb=1]	265.535	29.911	938.180	.000	206.835	324.235
	[Verb=2]	101.124	29.387	883.091	.001	43.447	158.800
	[Verb=3]	276.434	27.009	654.484	.000	223.399	329.469
36	[Verb=1]	-101.758	28.321	776.037	.000	-157.352	-46.164
	[Verb=2]	41.926	29.453	889.953	.155	-15.880	99.732
	[Verb=3]	6.735	28.088	753.662	.811	-48.405	61.876
37	[Verb=1]	-205.460	28.026	747.704	5.937E-13	-260.478	-
							150.441
	[Verb=2]	-200.003	28.854	828.691	8.369E-12	-256.639	-
							143.368
	[Verb=3]	-184.093	23.837	410.039	8.790E-14	-230.951	-
							137.235
38	[Verb=1]	46.565	28.798	823.082	.106	-9.961	103.092
	[Verb=2]	1.912	28.122	756.900	.946	-53.295	57.118
	[Verb=3]	41.625	24.762	473.990	.093	-7.032	90.283
39	[Verb=1]	127.351	31.213	1081.529	4.834E-5	66.105	188.596
	[Verb=2]	52.921	28.855	828.772	.067	-3.715	109.558
	[Verb=3]	103.984	28.531	796.618	.000	47.979	159.989
40	[Verb=1]	-199.040	28.073	752.261	3.095E-12	-254.151	-
							143.928
	[Verb=2]	-250.684	28.074	752.272	.000	-305.796	-
							195.573
	[Verb=3]	-149.631	24.282	440.020	1.621E-9	-197.354	-
							101.909
41	[Verb=1]	-.932	28.320	775.981	.974	-56.525	54.660
	[Verb=2]	229.455	28.634	806.748	4.000E-15	173.249	285.661
	[Verb=3]	172.511	25.857	557.482	6.107E-11	121.721	223.300
42	[Verb=1]	-57.833	28.633	806.706	.044	-114.038	-1.628
	[Verb=2]	-40.494	28.171	761.564	.151	-95.795	14.807
	[Verb=3]	31.293	24.805	477.091	.208	-17.448	80.033
43	[Verb=1]	217.584	34.200	1436.014	2.668E-10	150.497	284.670
	[Verb=2]	112.720	28.911	834.469	.000	55.972	169.468
	[Verb=3]	164.107	29.915	938.641	5.296E-8	105.399	222.816
44	[Verb=1]	276.772	30.339	984.288	.000	217.236	336.307

	[Verb=2]	119.227	28.742	817.531	3.703E-5	62.809	175.644
	[Verb=3]	284.103	26.407	602.656	.000	232.241	335.964
45	[Verb=1]	-32.811	29.084	851.990	.260	-89.897	24.274
	[Verb=2]	-103.339	27.931	738.769	.000	-158.173	-48.504
	[Verb=3]	-72.158	25.505	529.697	.005	-122.261	-22.055
46	[Verb=1]	148.146	29.203	864.136	4.796E-7	90.828	205.463
	[Verb=2]	67.898	27.885	734.396	.015	13.154	122.642
	[Verb=3]	202.191	26.309	594.434	6.350E-14	150.521	253.861
47	[Verb=1]	42.298	28.800	823.236	.142	-14.231	98.827
	[Verb=2]	-5.144	29.775	923.744	.863	-63.579	53.291
	[Verb=3]	60.836	24.889	483.229	.015	11.932	109.741
48	[Verb=1]	-83.349	29.026	846.059	.004	-140.321	-26.378
	[Verb=2]	-168.968	27.931	738.768	2.309E-9	-223.803	-114.134
	[Verb=3]	-106.128	25.428	523.724	3.509E-5	-156.080	-56.175

**Table S3**

**Effect of the stimulation factor in an additional LMM in which stimulation condition was analyzed as a random slope in the by-subject intercept**

95% confidence interval

Parameter <sup>a</sup>	Estimate	Dev. Error	Wald Z	Sig.	Lower limit	Upper limit
Residue	76768.5083	674.033586	113.894	.000	75458.728893	78101.022407
Stimulation [Subject = Subject variance]	26541.5726	3210.136382	8.268	.000	20939.965872	33641.653707

a. Dependent variable

Type III Tests of Fixed Effects<sup>a</sup>

Source	Numerator degree freedom	Denominator degree freedom	F	Sig.
Intercept	1	141.986	5045.143	.000
Hand	1	141.986	1.103	.295
Verb	2	25950.445	117.309	.000
Hand * Verb	2	25950.445	1.069	.344

a. Dependent variable

**Table S4**

**Error rate (ER) for each stimulation condition, hand, and verb category. Differences in ER between anodal and sham stimulation condition were not significant in any case ( $p > 0.05$ ).**

	RH Broca		LH Broca		RH Wernicke		LH Wernicke				
	Anodal	Sham	Anodal	Sham	Anodal	Sham	Anodal	Sham			
<b>Movement</b>	4.85	5.21	<b>Movement</b>	4.26	4.62	<b>Movement</b>	3.79	5.33	<b>Movement</b>	5.09	4.62
<b>Emotional</b>	4.5	4.73	<b>Emotional</b>	5.21	4.97	<b>Emotional</b>	3.79	5.56	<b>Emotional</b>	5.45	3.55
<b>Neutral</b>	5.09	4.73	<b>Neutral</b>	4.73	4.85	<b>Neutral</b>	4.5	4.62	<b>Neutral</b>	4.85	5.09

*Note.* RH = right hand; LH = left hand