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Short communication

Anodal transcranial direct current stimulation over left inferior frontal gyrus enhances sentence comprehension

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A R T I C L E I N F O

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A B S T R A C T

We tested the possibility of enhancing natural language comprehension through the application of anodal tDCS (a-tDCS) over the left inferior frontal gyrus, a key region for verbal short-term memory and language comprehension. We designed a between subjects sham- and task-controlled study. During tDCS stimulation, participants performed a sentence to picture matching task in which targets were sentences with different load on short-term memory. Regardless of load on short-term memory, the Anodal group performed significantly better than the Sham group, thus providing evidence that a-tDCS over LIFG enhances natural language comprehension.

To our knowledge, we apply for the first time tDCS to boost sentence comprehension.

This result is of special interest also from a clinical perspective: applying a-tDCS in patients manifesting problems at the sentence level due to brain damage could enhance the effects of behavioral rehabilitation procedures aimed to improve language comprehension.

1. Introduction

Transcranial direct current stimulation (tDCS) is a non-invasive neuromodulatory technique that uses a weak constant direct current to modify the spontaneous firing rate of neurons in a polarity-dependent way: anodal tDCS (a-tDCS) depolarizes membrane potential, while cathodal tDCS yields to opposite effects (Bindman, Lippold, & Redfearn, 1964; Purpura & McMurtry, 1965).

As reviewed in Monti et al. (2013), tDCS has been applied successfully in several works aimed at studying language processing in healthy individuals. Among others, a-tDCS has been shown to improve verbal fluency (Cattaneo, Pisoni, & Papagno, 2011; Iyer et al., 2005), word retrieval (Fiori et al., 2011) picture naming (Fertonani, Rosini, Cotelli, Rossini, & Miniussi, 2010; Holland et al., 2011; Sparing, Dafotakis, Meister, Thirugnanasambandam, & Fink, 2008), verbal learning (Flöel, Rösser, Michka, Knecht, & Breitenstein, 2008), and artificial grammar learning (De Vries et al., 2010).

Furthermore, single sessions of a-tDCS have been reported to affect performance of healthy subjects in tasks tapping working memory (Brunoni & Vanderhasselt, 2014). Specifically, a-tDCS stimulation over the dorsolateral prefrontal cortex has been found to enhance working memory performance, as measured by a sequential-letter working memory task (e.g. Fregni et al., 2005).

Still, to our knowledge no study has ever been devoted to exploring tDCS effects at the sentence level. This gap in the existing literature prompted us to investigate whether anodal tDCS may indeed boost sentence comprehension.

Sentence comprehension involves a complex interaction of cognitive abilities (phonological skills, word decoding, morpho-syntactic processing, pragmatic abilities etc.) and, in principle, the effects of tDCS on each of these components might be the topic of a separate study. However, we decided to start our investigation on the enhancing role of tDCS (if any) by focusing on another essential cognitive component for sentence comprehension, namely working memory resources. We did that because their role in language comprehension has been studied fairly extensively with neurostimulation techniques other than tDCS, as we are going to report, so we could build on findings emerging from these previous studies.

It is uncontroversial that language comprehension requires memory resources, either related to the length of the sentence (e.g. "*Yesterday the sun was shining and I went to the park with my cousin Mario*"), or to syntactic complexity, and specifically to the presence of long-distance

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dependencies. For example, in a sentence like "*The dog that the boy is watching is chasing the cat*", the relative clause < that the boy is watching > is embedded within the main sentence. This means that, in order to correctly understand the sentence, the matrix subject < the dog > , uttered before the relative clause, has to be retained in memory until the predicate < is chasing the cat > has been uttered (i.e., after the relative clause).

Memory resources involved in language comprehension might be those identified as the Phonological Loop in Baddeley and Hitch's (1974) model, namely the limited capacity verbal short-term memory system (VSTM) in which verbal information is temporarily held and manipulated during cognitive tasks that require its maintenance. These resources should be the same used in non-syntactic tasks execution, i.e. remembering lists of digits (Baddeley, 2003; See Fedorenko, Gibson, & Rohde, 2006; Just & Carpenter, 1992; and Romero Lauro, Reis, Cohen, Cecchetto, & Papagno, 2010). Alternatively, other authors suggested that memory resources involved in comprehension might be a separate and specialized subset devoted to syntactic and semantic sentence processing (Caplan & Waters, 1999; Makuuchi, Bahlmann, Anwander, & Friederici, 2009). While this debate is still open, the involvement of short-term memory resources if the sentence is sufficiently long or complex is not controversial, so boosting these short-term memory resources by tDCS might be a way to improve sentence comprehension.

Studies exploring the neural correlates of VSTM reported the involvement of the Left Inferior Frontal Gyrus (LIFG). Specifically, neuropsychological reports (for a review see Vallar & Papagno, 2002), neuroimaging (Awh et al., 1996; Henson, Burgess, & Frith, 2000; Hinke et al., 1993; Paulesu, Frith, & Frackowiak, 1993) and brain stimulation (Romero Lauro, Walsh, & Papagno, 2006) studies suggest an involvement of left BA44 (pars opercularis) on articulatory rehearsal. For example, in an fMRI study Paulesu et al. (1993) compared the subjects' performance in a rhyming judgement task, in which English stimuli were visually presented, hence requiring the subvocal rehearsal system, with a control task in which the stimuli consisted of Korean letters that cannot be to transcoded phonologically. The subtraction between this two tasks revealed a significant activation in BA44, indicating this region as the neural correlate of articulatory rehearsal. Analogously, disrupting the activity of the same region by 5-Hz repetitive rTMS resulted in a lower performance in two phonological judgement tasks (an initial sound similarity task and a stress assignment task), both engaging articulatory rehearsal, as compared with a visual pattern span as control task (Romero Lauro et al., 2006).

Furthermore, LIFG has been described as the locus for syntax specific aspects of language (e.g. Makuuchi et al., 2009), suggesting its involvement in complex sentence comprehension (for a review see Friederici, 2011).

In a previous study of Romero Lauro et al. (2010), 1 Hz offline rTMS over BA44 (neural correlate of rehearsal) reduced accuracy only on syntactically complex sentences whereas rTMS over BA40 (neural correlate of short-term storage) reduced accuracy on both complex sentences and long but syntactically simple sentences. Based on this study, we hypothesize that increasing memory resources involved in rehearsal by applying online a-tDCS over LIFG, and specifically over BA 44 might *selectively* enhance comprehension of syntactically complex sentences. Therefore, in addition to addressing our main research question (whether it is possible to improve sentence comprehension by means of tDCS), we aimed at detecting which kind of syntactic structures, if any, can be improved, focusing on sentences involving different degrees of short-term memory load and syntactic complexity.

In addition to online effects occurring during stimulation, tDCS might lead to long-term effects, likely mediated by synaptic plasticity. This fostered the use of the technique in rehabilitative settings (Lefaucheur et al., 2017). Therefore, any result showing that a-tDCS can improve sentence comprehension might be of great interest from the neuro-rehabilitation perspective.

2. Methods

2.1. Participants

Forty-four healthy young participants (12 male and 32 female; mean age = 22, SD = 2) took part in the study. Half of them received tDCS anodal stimulation (Anodal Group) and half of them received sham/placebo stimulation (Sham Group). All participants were naïve to the procedure of the study and they were not informed about the purpose of the experiment until the final debriefing.

Each participant completed an Adult Safety Screening Questionnaire (Keel, Smith, & Wassermann, 2001) and gave informed written consent prior to study procedures. Participants with any contraindication to tDCS procedures were excluded (Rossi, Hallett, Rossini, Pascual-Leone, & Safety of TMS Consensus Group, 2009).

All participants declared to be right-handed, this was confirmed by the Edinburgh Handedness Inventory (Oldfield, 1971) for all participants (mean laterality coefficient = 0.78, SD = 0.15) except one (laterality coefficient = 0.4). This participant was assigned to the Sham Group; the other participants were randomly divided between the Sham and the Anodal groups.

Participants were all Italian native speakers.

The study was approved by the local Ethical Committee.

2.2. tDCS procedure

TDCS was delivered using a BrainSTIM stimulator (EMS) through two electrodes: to stimulate BA44, the anode electrode was placed over F5 according to the 10–20 international system for EEG electrodes placement, while the cathode was placed over the contralateral supraorbital area.

The anode was 9 cm^2 (3 × 3 cm) whereas the cathode was 35 cm^2 (7 × 5 cm), in order to increase the focality of the stimulation (Nitsche et al., 2008). A constant current of 0.75 mA intensity was applied for 30 min. For the sham condition, the stimulator turned off automatically after 30 s; this procedure has been shown to be effective in blinding participants from their assigned condition (sham vs real tDCS) (Ambrus et al., 2012; Gandiga, Hummel, & Cohen, 2006; Woods et al., 2016). Indeed, the sham stimulation included, as the real condition did, a ~10 s fade-in and a fade-out phases at the beginning and at the end of the protocol, in which current ramped on and off. The ramp-in and ramp out phases are the only periods during the stimulation in which itching sensations on the skin are perceived by the subjects, thus making the two conditions undistinguishable for naïve subjects as those enrolled in our experiment (Nitsche et al., 2003; Paulus, 2003).

The experiment started 10 min after stimulation onset and lasted until the end of stimulation (Boggio et al., 2008). In order to standardize the procedure during the first ten minutes of tDCS participants watched two silent cartoon videos of 5 minutes each.

Half of the participants began with the Linguistic Task, and half with the Control task.

2.3. Materials and procedure: linguistic task

Stimuli were 90 pre-recorded sentences in Italian, each one followed by two pictures. One picture correctly displayed the sentence meaning, the second picture showed the same characters playing a different role in the same event. Both sentences and pictures came from the standardized test "COMPRENDO" (Cecchetto, Di Domenico, Garraffa, & Papagno, 2012). Target sentences (N = 54) could be of three types: a) coordinate sentences (Coord, e.g. "*The boy is watching the cat and the woman is caressing the dog*") and two groups of sentences with relative clauses: b) relative clauses in center embedded position (Rel_CE: subject relatives, e.g. "*The dog that is chasing the cat is watching the girl*" and object relatives, e.g. " *The man whom the woman is watching is eating pasta*") and c) relative clauses in the right peripheral position (Rel_RP: