Dorsolateral pFC and the Representation of the Incorrect Use of an Object: The Transcranial Direct Current Stimulation Effect on N400 for Visual and Linguistic Stimuli

Michela Balconi and Silvia Vitaloni

Abstract

In this study, we explored the representation of an incongruent action (instrumentally incorrect use of an object) in comparison with sentences ending with an incongruent action word, taking into account the role of the activation of the left dorsolateral pFC (DLPFC). This activity was appositely modulated by transcranial direct current stimulation (tDCS). The effect of tDCS when participants processed congruent/incongruent object-related actions (Experiment 1) or sentences (Experiment 2) was verified by measuring changes in the ERP N400, error rates (ERs), and RTs. In Experiment 1, 30 participants performed the detection task within a dynamic context (video tapes representing a sequence of four action frames). In Experiment 2, 28 participants read sentences that represented object-related actions. The stimulation effect (a cathode applied to the DLPFC and an anode to the right supraorbital region) was analyzed by comparing the ER, RT, and ERP profiles before and after stimulation (or sham treatment). A significant reduction of the N400 was observed for incongruent stimuli in the case of cathodal (inhibitory) stimulation of the DLPFC in comparison with prestimulation conditions for Experiment 1, but not Experiment 2. Moreover, ERs were increased, and RTs were reduced in response to incongruent conditions after tDCS, but not after sham stimulation in Experiment 1. It is suggested that perturbation of the DLPFC may limit the ability to analyze a semantically anomalous action sequence as a reduced N400 ERP effect and increased random responses was observed. Finally, the contribution of the frontal area to the semantic processing of actions is discussed.

INTRODUCTION

This study explored the contribution of a specific frontal cortical area to the processing of object-related actions within a visual (action frames) or linguistic (sentences) context. Specifically, the cortical response to congruent versus incongruent object-related actions was analyzed by measuring ERP and behavioral (error rates [ERs], RTs) changes (Experiment 1). A second experiment (Experiment 2) was conducted to verify the semantic specificity of these modulations by considering congruent versus incongruent action-related sentences. To explore the specific role of the frontal cortical area in action representation, we induced a transitory inhibitory effect in the dorsolateral pFC (DLPFC), comparing the behavioral and ERP profiles in the presence or absence of transcranial direct current stimulation (tDCS; cathodal stimulation).

It was shown that tDCS may have a significant impact on the EEG profile, specifically on oscillatory activity (Pellicciari, Brignani, & Miniussi, 2011; Brignani, Pellicciari, & Miniussi, 2010; Ardolino, Bossi, Barbieri, & Priori, 2005; Marshall, Mölle, Hallschmid, & Born, 2004). Other studies have noted the significant modifications induced by current stimulation in ERP deflections (Keeser et al., 2011). One recent study also showed the specific relevance of the effect of tDCS on the learning of an action lexicon (Luiuzzi et al., 2010).

Nevertheless, no previous study has explored the efficacy of tDCS in inducing EEG/ERP modulation in the case of action comprehension, taking into account the specific effect on N400. A previous experiment was conducted to explore the cortical generators of the perception of action incongruence using a frequency band analysis approach (Balconi & Vitaloni, 2012). It was mainly focused on the alpha band distribution to test the main contribution of frontal versus posterior sites in semantic anomaly perception in response to action sequences. A significant contribution by prefrontal areas in semantic processing was found. However, first, these results did not allow a direct comparison between action and language representation in cases of a semantic incongruence, because this study did not explore the effect of tDCS on the specific linguistic-related ERP deflection, that is, the N400 effect. Second, this previous study was mainly finalized to verify the effect of the tDCS approach on cortical oscillations, without a clear focus on a specific temporal window; in contrast, the present research considered the neuro-modulation effect on DLPFC exclusively related to a time interval where the ERP phenomenon was expected to be present. Thus, a systematic analysis about the cortical

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localization of action processing in comparison with language processing is required to verify their resemblance or differences.

In fact, it was shown that the N400 ERP deflection is a negative waveform that peaks at approximately 400 msec after the onset of a stimulus. Its amplitude is larger for critical words that are semantically unrelated to preceding words (Balconi & Pozzoli, 2003, 2004; Bentin, McCarthy, & Wood, 1985), incongruent with the context of a sentence (Balconi & Pozzoli, 2005a, 2005b; Kutas & Hillyard, 1980), and unusual with respect to semantic expectancies (contextual constraints; Kutas & Hillyard, 1984), or that violate previously stored semantic information (Hagoort, Hald, Bastiaansen, & Petersson, 2004).

Recent research also considered the N400-like effect induced by a semantic action domain. Indeed, action comprehension has been observed as a specific type of semantic processing wherein context–action representation results in integration, as in word–sentence representations. In fact, it was shown that, as in language comprehension, increasing N400 amplitudes were registered in the case of objects that were incongruent with a picture/object prime, within the context of a background scene or within the context of a verbal sentence (Balconi & Caldiroli, 2011; Federmeier & Kutas, 2001).

The aim of the present research was to investigate the impact of tDCS on the behavioral and N400 effects when neuromodulation was produced in the DLPFC. First, we sought to analyze the direct effect of tDCS on the ERP profile in response to a semantic task. Two different tasks were examined: a first object-related action representation induced by an action sequence (Experiment 1) and a second object-related action representation induced by a sentence (Experiment 2). The two experiments were realized to demonstrate the specificity of the left DLPFC in the semantic processing of action observations. Thus, we expected that, in the case of perturbation of this semantic processing induced by tDCS cathodal stimulation, a significant reduction of the N400 peak amplitude would be revealed in response to the incongruent conditions only for the action observation task.

To explore this topic, we first provided a specific context in our experiments, where the final frame of a sequence of actions represented a congruent/incongruent ending or the final word of a sentence induced a congruent/incongruent action representation. Object-related actions were displayed that were either correct or incorrect, in which an anomalous way to use an object with respect to the context was represented; that is, the object was incorrectly used to perform the action in overt violation of the instrumental object-related properties (using a brush in an up–down direction or using an iron to water flowers). Thus, the action was in opposition to the goal-related and intention-related requirements to perform that action (van Dam, Rueschemeyer, Lindemann, & Bekkering, 2010).

Whereas previous studies have investigated only general aspects of motor action, such as the gesture–context coherence or object manipulation tasks within a single frame (Proverbio, Riva, & Zani, 2010; van Elk, van Schie, & Bekkering, 2010), in Experiment 1, we aimed to analyze an ERP marker of action representation by providing a specific sequential frame wherein an object-related action was performed. Previous results related to action processing have been intriguing, but as these results were obtained for a single action, the possibility cannot be ruled out that they reflect only the quality of the action performed rather than the dynamic action-related representation induced by the violation of action–object or action–context constraints. Whereas previous studies have included isolated hand or mouth movements (Aravena et al., 2010; Bach, Peelen, & Tipper, 2010; Bach, Gunter, Knoblich, Prinz, & Friederici, 2009), in the present research, complex scenes depicting persons engaged in congruent or incongruent actions with respect to a given context were provided. In Experiment 2, the semantic action representation induced by congruent versus incongruent sentences was analyzed, considering the modulation of the N400 effect induced by tDCS when a linguistic task was performed. These results were compared directly with those of Experiment 1 to verify the specific effect of the left DLPFC on the processing of an action induced by visual frames.

Another main point to be clarified concerns the cortical generators of this semantic process in the case of action representation in comparison with the response to a generic semantic incongruence. Neuroimaging studies performed during the comprehension of action execution have implicated a broad network of cortical regions in the processing of semantic relationships. Generally, stimuli that cannot be mapped on the semantic memory networks accessed by the preceding context evoke an increased response within the left inferior prefrontal and temporal cortices (Friederici, Rueschemeyer, Hahne, & Fiebach, 2003). Names or pictures of real-world objects and goal-directed actions activate overlapping brain regions in the temporal, parietal, and premotor areas (Balconi & Vitaloni, 2012; Balconi & Caldiroli, 2011; Kemmerer, Castillo, Talavage, Patterson, & Wiley, 2007). In addition, inappropriate tool use actions produce a more left-lateralized N400 (Bach et al., 2009). Regarding the N400, it was shown that this effect tends to show a more anterior distribution when processing picture stimuli (West & Holcomb, 2002; Barrett & Rugg, 1990) in comparison with linguistic tasks. This anterior negativity (the N400-like effect) was assumed to reflect image or action-specific semantic processing that could be functionally similar to the processing of linguistic semantic anomalies indexed by a parietal N400 component.

Neuroimaging and electrophysiological studies have linked prefrontal activity (and specifically DLPFC activity) to integration between objects and actions based on goal-related features. Specifically, the left DLPFC was shown to be activated when participants decided whether two objects fit the requirements of a given action (Bach et al., 306 Journal of Cognitive Neuroscience Volume 26, Number 2
In particular, based on previous band analysis research, we may suppose that the cortical generators of semantic action representation may be related to the pFC when an anomalous sequence is produced (Balconi & Vitaloni, 2012). However, because of the consistent differences in the methodological approach adopted in this previous research with respect to the present one (ERP vs. band analysis) and the probable independence of the brain oscillation variations from the ERP modulations in response to tDCS effect, these results may be only partially useful to explain the resemblance between action and linguistic domain.

Therefore, because of the heterogeneity of previous research findings, the cortical generators of the semantic processing of congruent/incongruent action representations should be more thoroughly explored. Moreover, the contribution of specific cortical sites, such as the left DLPFC, to the comprehension of object-related actions must be verified. In this study, we assumed that tDCS of the anterior DLPFC area might induce a decreased ability to produce a concomitant N400 effect because this area should be recruited to elaborate the semantic meaning of an action when an incorrect use is displayed. This could be based on the fact that the DLPFC, particularly the left side of the pFC, is causally determinant in the generation of a semantic response of congruence/incongruence in the case of visual action representation. In addition, we expected the participants to perform generally worse when DLPFC was inhibited for visual stimuli in comparison with verbal stimuli because of the specificity of the DLPFC for visual semantic processing. A specific neural source estimation (low-resolution electromagnetic tomography [LORETA]) was used to systematically examine and compare brain responses when action was comprehended under the two conditions (congruent vs. incongruent condition).

**METHODS**

**Participants**

In Experiment 1, 30 undergraduate students took part in the experiment (18 women, age range = 20–28 years, \( M = 24.22 \) years, \( SD = 2.77 \) years). The participants were all right-handed and presented normal or corrected-to-normal visual acuity. They gave informed written consent to participate in the study, and the research was approved by the local ethics committee of the Department of Psychology, Catholic University of Milan. Exclusion criteria were a history of psychopathology in the participants or their immediate family. In Experiment 2, 28 undergraduate students took part in this experiment (14 women, age range = 20–27 years, \( M = 24.18 \) years, \( SD = 2.13 \) years). They were all right-handed and presented normal or corrected-to-normal visual acuity (Figure 1).

**Stimuli**

For Experiment 1, three sets (which were distinct for Phases 1 and 2 of the experiment; see the Procedure section) of 60 action sequences (each composed of four frames) were presented to the participants, with a congruent (30 sequences) or incongruent (30 sequences) final frame (final target action frame). The stimulus sequences were constructed, taking into account some general data sets previously validated (Balconi & Vitaloni, 2012; Balconi & Caldiroli, 2011). Frames (color photographs obtained using a digital Canon and edited using Adobe Premier 6.0 software) subtending 4° of the visual angle and centered on a black background were shown without sound for 1.5 sec, with an ISI of 250 msec, being careful to ensure that the scene change would appear natural to reproduce a similar-to-real-world sequence. Each frame was composed of a real-world scene that represented a
participant and an object within a neutral background (a neutral room without other relevant objects). The background was maintained the same for all sequences to avoid an uncontrolled effect because of background perceptual variability. The average luminance and contrast in the scenes in the congruent and incongruent conditions did not vary because the same pictures were used (see Figure 2 for an example). The semantic anomaly consisted of an object that was not correctly used (incorrect) with respect to the instrumental properties required for the central action-goal (grasping a bat upside-down). The inter-sequence interval was 5 sec.

Each sequence was evaluated in a pre-experimental phase by a specific group of participants. A group of 15 healthy participants (seven women; age mean = 22.87 years, SD = 2.03 years) viewed each congruent/incongruent sequence, and they were asked to evaluate the sequences with respect to the semantic properties required for the central action-goal (grasping a bat upside-down). The inter-sequence interval was 5 sec.

Figure 2. ERP waveforms for congruent and incongruent conditions. A higher peak N400 was observed for the frontal localization.

Only the sequences that were evaluated coherently with the experimental requests (highly semantically incongruent, $M = 1.58$, $SD = 0.33$; not pertinent, $M = 2.87$, $SD = 0.20$; and unexpected, $M = 2.38$, $SD = 0.38$ for the incongruent vs. semantically congruent condition, $M = 6.11$, $SD = 0.11$; pertinent, $M = 6.27$, $SD = 0.25$; and expected, $M = 6.02$, $SD = 0.39$ for the congruent conditions and with a Cronbach’s alpha range of 0.69–0.86) were included in the final data set (approximately 10% of the initial material was discarded from the final material). Each sequence was considered highly familiar ($M = 5.70$, $SD = 0.23$ for congruent; $M = 5.69$, $SD = 0.31$ for incongruent; “how much do you consider common and daily this action?”), measured on a 7-point Likert scale and concrete ($M = 5.66$, $SD = 0.18$ for congruent; $M = 5.72$, $SD = 0.32$ for incongruent), with respect to its content (“how do you consider this action a concrete object-related action?”). For each set of stimuli, the material in the scenes was then organized into two identical sets, each including half congruent and half incongruent ending frames. Each set contained only one of the two versions of the final target action frame, and these versions differed only regarding the use of the same object. The first three frames were identical across the two sets. Half of the participants viewed Set 1, and half viewed Set 2. The order of the sequence was counter-balanced across participants.
For Experiment 2, three sets (distinct for Phases 1 and 2 of the experiment, see the Procedure for Experiment 1) of 80 sentences were presented to the participants with a congruent (40 sequences) or incongruent (40 sequences) ending. The stimulus materials consisted of a set of sentences in which each sentence consisted of four words (subject + predicate + substantive + infinite predicate), such as “Marta usa il ferro da stiro per stire” [“Marta uses an iron for ironing”] for the congruent condition or “Marta usa il ferro da stiro per annaffiare” [“Marta uses an iron for watering”] for the incongruent condition. Thus, we obtained two versions of the same sentence that were identical except for the ending. The sentences expressed sufficient context to be interpreted with no additional information required, and the congruent/incongruent word was always the last one in the sentence. The frequency of final word occurrence and word length were monitored across the experimental conditions (Burani, Barca & Arduino, 2001; De Mauro, Mancini, Vedovelli, & Voghera, 1993). Moreover, because of the effect of concrete/abstract contents, the targets were balanced with respect to these two categories of words. Each sentence was evaluated in a pre-experimental phase. A group of 10 participants (six women; mean age = 23.45 years, \(SD = 1.89\) years) were asked to evaluate the provided sentences with respect to their semantic congruence, pertinence, and degree of the expectancy (each on a 7-point Likert scale, see Procedure section). Only the sentences that were evaluated coherently with respect to the experimental requests (highly semantically incongruent, \(M = 1.50, SD = 0.38\); not pertinent, \(M = 2.81, SD = 0.20\); and unexpected, \(M = 2.10, SD = 0.27\)) for the incongruent condition vs. semantically congruent, \(M = 6.54, SD = 0.18\); pertinent, \(M = 6.32, SD = 0.20\); and expected, \(M = 6.30, SD = 0.41\)) for the congruent condition, with a Cronbach’s alpha range of 0.62-0.85) were included in the final sets (approximately 7% of the initial material was discarded from the final material). For each set of stimuli, the sentence material was then organized into two identical sets, each consisting of half congruent and half incongruent ending. Each set contained only one of the two versions of the sentence, and these versions differed only in the final word. Half of the participants viewed Set 1, and half viewed Set 2. The order of the sequence was counterbalanced across participants.

Procedure

The procedure was subdivided into three phases. Before tDCS, a baseline task was performed on a separate day, and an EEG was registered (Phase 1, baseline task). The participants were required to press the left or right button (counterbalanced across the participants) of a mouse depending on whether the final action target frame represented a congruent or an incongruent ending scene. The stimulus material was presented on a PC monitor (by using the software STIM 2.2), and the participants sat on a comfortable chair in front of the PC. They were instructed to gaze at the center of the screen, where a small cross served as fixation point. They were also required to minimize blinking. A familiarization phase preceded the experimental phase, where the participants experienced a practice run to familiarize them with the stimulus material and the overall procedure. The material used during the familiarization phase was not displayed again in the successive phases.

For Experiment 2, stimuli were presented one word at a time in the center of the screen, and each word was displayed in white letters (Times New Roman font, letter size of 3 cm) against a dark background. The duration of the stimulus was 600 msec, with an ISI of 400 msec. The intersentence length was constant (5 sec). A small cross was presented before the target in the center of the screen indicating the position of the final word. The participants were required to press the left or right button (counterbalanced across the participants) of a mouse depending on whether the final word represented a congruent or an incongruent ending. They were also required to minimize blinking. A familiarization phase preceded the experimental phase, in which the participants experienced a practice run to familiarize them with the stimulus material and the overall procedure. The material used during the familiarization phase was not presented again in the successive phases. Subsequently (at least 2 days after Phase 1), in the same room as Phase 1, tDCS/sham stimulation was induced (Phase 2) in the participants via battery-driven, constant current stimulation through a pair of saline-soaked sponge electrodes \((7 \text{ cm} \times 5 \text{ cm})\) with a horizontal orientation. A constant current of 2 mA was applied for 15 min.

The cathode was placed above the left DLPFC, with the center above F3 and the anode above the right supraorbital region. F3 localization has been used to modulate the left DLPFC (Balconi & Ferrari, 2012). BA 9 was assumed to be directly modulated by the effect of tDCS. For the sham tDCS, a custom-built placebo stimulator was used, which was indistinguishable from the active tDCS device, as the participants did not report any differences between the two conditions (no different sensation). As shown in previous studies, cathodal stimulation is generally able to induce an inhibitory effect on the cortical side where it is applied (Jacobson, Koslowsky, & Lavdor, 2012). The impedance was controlled by the device, normally falling below 5 k\(\Omega\). All participants underwent single sessions of active tDCS and sham tDCS in a randomized order, with both conditions being counterbalanced across participants. tDCS and sham sessions were performed on the same day (with a mean temporal interval of 3 hr). Finally, immediately after tDCS/sham stimulation (10 min later; Phase 3, poststimulation task), the participants were subjected to the same experimental task as in Phase 1. EEG recordings were performed successive to the tDCS/sham stimulation, without montage interference.

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between the two phases (no interference or superimposition effect of tDCS on EEG). The EEG was registered during task execution using the same EEG acquisition procedure adopted in Phase 1.

**EEG Recordings**

EEG recordings were performed with a 64-channel DC amplifier (Synamps system, Charlotte, NC) and acquisition software (Neuroscan 4.2, Charlotte, NC) during task executions (Phases 1 and 3 of the experiment). An Electro-Cap with Ag/AgCl electrodes was used to record EEGs from active scalp sites referred to the earlobes (10/20 system of electrode placement; Jasper, 1958). Data were acquired using a sampling rate of 500 Hz, with a frequency band of 0.01–50 Hz (Sitnikova, Holcomb, Kiyonaga, & Kuperberg, 2008). An off-line common average reference was successively computed to limit the problems associated with the signal-to-noise ratio (Ludwig et al., 2008). Additionally, two EOG electrodes were sited on the outer canthi to detect eye movements. The impedance of the recording electrodes was monitored for the entire session to ensure accurate artifact-free EEG data. The electrical activity was recorded with a face-to-face arrangement of electrode placement; Jasper, 1958). An off-line common average reference was successively computed to limit the problems associated with the signal-to-noise ratio (Ludwig et al., 2008). Additionally, two EOG electrodes were sited on the outer canthi to detect eye movements. The impedance of the recording electrodes was monitored for the entire session to ensure accurate artifact-free EEG data.

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**RESULTS**

**Experiment 1**

**Phase 1 (Baseline Task)**

**Behavioral data.** RTs and ERs were subjected to a one-way repeated-measures ANOVA to examine Congruence (congruent vs. incongruent). Type I errors associated with inhomogeneity of variance were controlled by decreasing the degrees of freedom using the Greenhouse–Geisser epsilon. For RTs, a significant main effect was found for Congruence, $F(1, 29) = 10.09, p = .001, \eta^2 = .39$. Longer RTs were observed in response to incongruent than congruent conditions (Table 1A). Moreover, regarding ERs, none of the effects were statistically significant, $F(1, 29) = 1.09, p = .25, \eta^2 = .09$ (Table 1B).
ERP data. Morphological analysis of ERPs showed a significant negative deflection within the 300–400 msec temporal window. The ERP data were subjected to a three-way repeated-measures ANOVA, in which the factors Congruence (2) × Lateralization (3) × Localization (4) were applied to the peak deflection variable. Significant main effects were found for Congruence, $F(1, 29) = 9.08, p = .001, \eta^2 = .37$, and Congruence × Localization, $F(3, 29) = 7.70, p = .001, \eta^2 = .24$. On the contrary, Lateralization, $F(1, 29) = 1.02, p = .11, \eta^2 = .08$, and Localization, $F(1, 29) = 1.34, p = .10, \eta^2 = .10$, were not significant as well as all two- or three-way interactions (all $p > .05$). A higher ERP negativity was found in response to incongruent than congruent conditions (Table 2). Moreover, as shown by post hoc analysis (contrast analysis, with Bonferroni corrections for multiple comparisons), a more frontal than temporoparietal, $F(1, 29) = 8.16, p = .001, \eta^2 = .35$, or occipital, $F(1, 29) = 9.02, p = .001, \eta^2 = .36$, distribution was found for incongruent stimuli (Figure 2). No other paired comparison was statistically significant.

Source analysis. To estimate the localization of the source of the cortical differences between congruent/incongruent conditions, LORETA was performed. A significant difference was revealed between congruent versus incongruent conditions for the selected mean N410 peak. The algorithm localized the source of this differential activation to the DLPFC ($t = 4.70, p < .01$; BA 9, $x = 4, y = 45, z = 15$; presumably the medial frontal gyrus; Figure 3A). No other site was found to differentiate the two conditions.

Phase 3 (Poststimulation Task)

Behavioral data. The RT and ER data were subjected to a three-way repeated-measures ANOVA involving the factors Congruence (2), Order (2), and Stimulation (2). For RTs, only a significant Congruence × Stimulation interaction effect was found, $F(1, 29) = 7.65, p = .001, \eta^2 = .28$. The other main or interaction effects were not significant (all $p > .10$). Post hoc comparison revealed increased RTs associated with incongruent than congruent stimuli for the sham condition, $F(1, 29) = 9.11, p = .001, \eta^2 = .34$, whereas no significant differences were observed in the case of tDCS (Table 1A). Moreover, longer RTs were observed for incongruent stimuli in the case of sham stimulation than tDCS, $F(1, 29) = 7.71, p = .001, \eta^2 = .30$.

For the ER measure, significant differences were found for the Congruence × Stimulation interaction, $F(1, 29) = 7.32, p = .001, \eta^2 = .27$, whereas no other main or interaction effects were not significant (all $p > .20$). Post hoc comparison revealed increased ERs associated with incongruent than congruent stimuli for the sham condition, $F(1, 29) = 9.32, p = .001, \eta^2 = .34$, whereas no significant differences were observed in the case of tDCS (Table 1A). Moreover, increased ERs were observed for

# Table 1. Response Times (msec) for Pre- and Post-Stimulation Phase as a Function of Congruence Condition

<table>
<thead>
<tr>
<th>Congruence</th>
<th>Prestimulation</th>
<th>Poststimulation</th>
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<tbody>
<tr>
<td></td>
<td>Sham</td>
<td>tDCS</td>
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<tr>
<td>M (SD)</td>
<td>M (SD)</td>
<td>M (SD)</td>
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<tr>
<td>Congruence</td>
<td>270 12.90</td>
<td>274 13.45</td>
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<tr>
<td>Incongruence</td>
<td>340 17.34</td>
<td>285 18.16</td>
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</tbody>
</table>

# Table 2. Mean Peak Amplitude of N400 (Negative Values) as a Function of Congruence, Localization, and Lateralization

<table>
<thead>
<tr>
<th>Congruence</th>
<th>Frontal</th>
<th>Central</th>
<th>Temporoparietal</th>
<th>Occipital</th>
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<tbody>
<tr>
<td></td>
<td>Left</td>
<td>(SD)</td>
<td>Right</td>
<td>(SD)</td>
</tr>
<tr>
<td>Congruence</td>
<td>3.63a</td>
<td>1.04</td>
<td>3.76</td>
<td>1.30</td>
</tr>
<tr>
<td>Incongruence</td>
<td>4.41</td>
<td>1.06</td>
<td>4.66</td>
<td>1.16</td>
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*aμVolt.
ERP data. A negative deflection was observed within the 300–400 msec temporal window, similar to the previously analyzed N400 component (Phase 1), with higher peak amplitude occurring at approximately 410 msec. The ERP data were subjected to a five-way repeated-measures ANOVA, in which the factors Congruence (2) × Order (2) × Stimulation (2) × Lateralization (3) × Localization (4) were applied to the peak deflection.

Significant main effects were found for Congruence, $F(1, 29) = 8.80, p = .001, \eta^2 = .31$, Stimulation, $F(1, 29) = 8.44, p = .001, \eta^2 = .30$, and Localization, $F(4, 29) = 6.99, p = .001, \eta^2 = .28$ (Table 3). The interaction effects were also significant for Stimulation × Condition, $F(1, 29) = 8.70, p = .001, \eta^2 = .31$, and for Stimulation × Condition × Localization, $F(3, 29) = 7.09, p = .001, \eta^2 = .28$. No other main or interaction effect was statistically significant (all $p > .12$).

Specifically, a higher peak deflection was revealed in the case of sham stimulation compared with tDCS under incongruent conditions, $F(1, 29) = 7.16, p = .001, \eta^2 = .28$, whereas no significant differences were found in response to congruent stimuli, $F(1, 29) = 1.22, p = .13, \eta^2 = .12$. Moreover, whereas the congruent and incongruent conditions did not differ in the case of tDCS, $F(1, 29) = 1.20, p = .18, \eta^2 = .11$, a significantly greater deflection was revealed for incongruent conditions in the case of sham stimulation, $F(1, 29) = 7.98, p = .001, \eta^2 = .28$.

Regarding the three-way interaction, a greater N400 effect was observed in response to incongruent conditions within the frontal area in the case of sham stimulation in comparison with tDCS, $F(1, 29) = 8.57, p = .001, \eta^2 = .31$. Moreover, a higher peak amplitude was observed in

Table 3. Mean Peak Amplitude of N400 (Negative Values) as a Function of Condition, Congruence, Order, Localization, and Lateralization

<table>
<thead>
<tr>
<th>N400</th>
<th>Frontal</th>
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<th>Central</th>
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<th>Temporoparietal</th>
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<th>Occipital</th>
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<td>Left</td>
<td>Right</td>
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<tr>
<td>tDCS</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Congruence</td>
<td>3.56</td>
<td>1.12</td>
<td>3.80</td>
<td>1.22</td>
<td>3.68</td>
<td>1.25</td>
<td>3.40</td>
<td>1.45</td>
</tr>
<tr>
<td>Incongruent</td>
<td>3.65</td>
<td>1.30</td>
<td>3.65</td>
<td>1.21</td>
<td>3.90</td>
<td>1.13</td>
<td>3.75</td>
<td>1.32</td>
</tr>
<tr>
<td>Sham</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Congruence</td>
<td>3.50</td>
<td>1.34</td>
<td>3.69</td>
<td>1.22</td>
<td>3.70</td>
<td>1.29</td>
<td>3.61</td>
<td>1.48</td>
</tr>
<tr>
<td>Incongruent</td>
<td>4.34</td>
<td>1.40</td>
<td>4.62</td>
<td>1.26</td>
<td>3.66</td>
<td>1.28</td>
<td>3.77</td>
<td>1.50</td>
</tr>
</tbody>
</table>

Figure 3. (A–D) Results of the LORETA analysis. The image shows the LORETA slices in Talairach space for the estimated source of activation differences (incongruent compared with congruent).
response to incongruent stimuli within the frontal area in comparison with the temporoparietal, $F(1, 29) = 7.30, p = .001, \eta^2 = .29$, and occipital areas, $F(1, 29) = 7.43, p = .001, \eta^2 = .29$, in the case of sham stimulation.

Source analysis. Regarding LORETA, a significant difference between congruent versus incongruent conditions was revealed for sham stimulation. The algorithm localized the source of this differential activation to the pFC ($t = 4.95, p < .01$; presumably the medial frontal gyrus, BA 9 $x = 4, y = 45, z = 15$; Figure 3B). No other effect was significant for tDCS condition.

Experiment 2

Phase 1 (Baseline Task)

Behavioral data. RTs and ERs were subjected to a one-way repeated-measures ANOVA involving the factor Congruence (congruent vs. incongruent). Regarding RTs, a significant main effect was found for Congruence, $F(1, 27) = 10.34, p = .001, \eta^2 = .30$, with longer RTs observed in response to incongruent than congruent conditions. No significant effects were detected for ERs (Table 1A, B; all $p > .18$).

ERP data. Morphological analysis of the ERPs showed a significant negative deflection within the 300–400 msec temporal window (mean latency, 420), as shown in Experiment 1. The peak data were subjected to a three-way repeated-measures ANOVA, with the factors Congruence ($2$), Order ($2$), and Stimulation ($2$). Significant main effects were found for Congruence, $F(1, 27) = 8.34, p = .001, \eta^2 = .31$ (Table 5). The Condition × Localization interaction effect was also significant, $F(3, 27) = 8.60, p = .001, \eta^2 = .31$. No other main or interaction effect was statistically significant (all $p > .38$). For RTs, the congruence effect was significant, $F(1, 27) = 7.65, p = .001, \eta^2 = .28$. Incongruent conditions elicited longer RTs than congruent conditions; no other effect was statistically significant (all $p > .35$). The ER measure did not show significant differences (all $p > .47$).

The RT and ER data were subjected to a three-way repeated-measures ANOVA involving the factors Congruence ($2$), Order ($2$), and Stimulation ($2$). On the contrary, the other two main effects (Order and Stimulation) as well as two-way and three-way interaction effects were not significant (all $p > .38$). For RTs, the congruence effect was significant, $F(1, 27) = 7.65, p = .001, \eta^2 = .28$. Incongruent conditions elicited longer RTs than congruent conditions; no other effect was statistically significant (all $p > .35$). The ER measure did not show significant differences (all $p > .47$).

Source analysis. LORETA revealed a significant difference between congruent versus incongruent conditions for the selected mean N420 peak. The algorithm localized the source of this differential activation ($t = 5.13, p < .01$) to the superior temporal gyrus (BA 22 $x = 60, y = −39, z = 15$) (Figure 3C).

Phase 3 (Poststimulation Task)

Behavioral data. The RT and ER data were subjected to a three-way repeated-measures ANOVA involving the factors Congruence ($2$), Order ($2$), and Stimulation ($2$). Regarding two-way interactions, a higher N400 effect was statistically significant ($p < .01$) to the superior temporal gyrus (BA 22 $x = 60, y = −39, z = 15$) (Figure 3C).

Source analysis. LORETA revealed a significant difference between congruent versus incongruent conditions for the selected mean N420 peak. The algorithm localized the source of this differential activation ($t = 5.13, p < .01$) to the superior temporal gyrus (BA 22 $x = 60, y = −39, z = 15$) (Figure 3C).

Table 4. Mean Peak Amplitude of N400 (Negative Values) as a Function of Congruence, Localization, and Lateralization

<table>
<thead>
<tr>
<th>N400</th>
<th>Frontal</th>
<th>Central</th>
<th>Temporoparietal</th>
<th>Occipital</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left (M, SD)</td>
<td>Right (M, SD)</td>
<td>Left (M, SD)</td>
<td>Right (M, SD)</td>
</tr>
<tr>
<td>Congruence</td>
<td>3.54 (1.34)</td>
<td>3.61 (1.05)</td>
<td>3.70 (1.18)</td>
<td>3.80 (1.13)</td>
</tr>
<tr>
<td>Incongruence</td>
<td>3.35 (1.09)</td>
<td>4.21 (1.44)</td>
<td>3.80 (1.48)</td>
<td>3.76 (1.67)</td>
</tr>
</tbody>
</table>
The comprehension of the action and linguistic anomaly (Experiment 1), inducing a significant distinction between but we also found that it was mainly frontally distributed present in case of semantic action anomaly perception, that a typical linguistic ERP deflection (the N400) was well-known effect of N400. In fact, not only did we find language semantic anomaly processing, considering the other action semantic anomalies tested by brain oscillations introduced an innovative approach by directly exploring (Balconi & Vitaloni, 2012). Indeed, this methodological option allowed for the present experiments produced some main findings, and here we report the principal results for Experiments 1 and 2.

The first significant effect of Experiment 1 was related to the frontal cortical contribution to the processing of an anomalous action representation. Specifically, object-related actions that did not adequately correspond to the associated requirements for an action (being anomalously used) evoked a significant negative deflection (N400) within the frontal area. On the basis of the localization data, the prefrontal site (medial frontal gyrus) was responsible for incongruence processing, as revealed by the presence of a more anteriorly distributed N400 effect. This area could support semantic anomaly representation for an object-related action inserted into sequential frames. This increased N400 effect for incongruent conditions was found in previous studies (Balconi & Caldiroli, 2011; Proverbio et al., 2010; Sitnikova et al., 2008). In another study, the DLPFC was found to be responsive to action semantic anomalies tested by brain oscillations (Balconi & Vitaloni, 2012). However, the present research introduced an innovative approach by directly exploring the effect of tDCS on the DLPFC within a specific time interval: the 300–450 msec successive to the anomaly presentation. This study differed from previous studies that used a brain oscillation approach (Balconi & Vitaloni, 2012). Indeed, this methodological option allowed for us to verify the direct relationship between action and language semantic anomaly processing, considering the well-known effect of N400. In fact, not only did we find that a typical linguistic ERP deflection (the N400) was present in case of semantic action anomaly perception, but we also found that it was mainly frontally distributed (Experiment 1), inducing a significant distinction between the comprehension of the action and linguistic anomaly (Experiment 2, see also the following paragraph for the discussion of this point).

These results allowed for us to extend the assumption of a generic frontal cortical generator for semantic action representation (as shown in previous experiments, Balconi & Vitaloni, 2012) to a specific context, when the action was analyzed as a “linguistic phenomenon” by focusing on a “linguistic” ERP effect. That is, in the present experiment, we directly verified the effect induced by the incongruous condition for both action and language representation. Whereas previous results tested the brain correlates of anomaly processing in the action condition, in this study, we explored the specific different cortical generators supporting action and language comprehension, respectively. In general, we may state that, when examining the increased demand of incongruent semantic relationships in the neurocognitive process, mapping the action on a semantic memory network could modulate the N400 effect. Thus, we may conclude that the N400 effect was evoked by the presence of inappropriate information in an action representation when goal-related requirements of the actions (violation of instrumental requirements and incorrect use of an object) were disregarded.

Moreover, as suggested by LORETA, this effect was localized to the frontal area. These results confirmed what was found in previous research (Balconi & Vitaloni, 2012) for actions, and they provide evidence that the pFC area was systematically involved in the detection of anomalies in action representation within a semantic context. Because of this anterior distribution of the N400 deflection in cases of action representation, tDCS stimulation may have exerted a significant effect where the peak deflection was observed. This mechanism involves a more anterior distribution than the classical brain activation induced by generic linguistic anomalies, where a more posterior distribution has been revealed (Balconi & Pozzoli, 2004; Friederici et al., 2003). As found in previous studies that compared linguistic tasks, objects, actions, or scene materials, an anteriorly localized cortical network might directly respond to an action representation.

### Table 5. Mean Peak Amplitude of N400 (Negative Values) as a Function of Condition, Congruence, Localization, and Lateralization

<table>
<thead>
<tr>
<th>Condition</th>
<th>Left M (SD)</th>
<th>Right M (SD)</th>
<th>Left M (SD)</th>
<th>Right M (SD)</th>
<th>Left M (SD)</th>
<th>Right M (SD)</th>
<th>Left M (SD)</th>
<th>Right M (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tDCS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Congruence</td>
<td>3.31 1.34 3.48 1.25</td>
<td>3.79 1.12 3.53 1.45</td>
<td>3.51 1.22 3.61 1.28</td>
<td>3.32 1.12 3.31 1.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incongruence</td>
<td>3.22 1.35 3.30 1.53</td>
<td>3.68 1.10 3.75 1.35</td>
<td>4.09 1.18 4.12 1.31</td>
<td>3.65 1.33 3.50 1.48</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sham</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Congruence</td>
<td>3.42 1.52 3.40 1.45</td>
<td>3.75 1.26 3.46 1.16</td>
<td>3.65 1.30 3.55 1.22</td>
<td>3.29 1.40 3.43 1.48</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incongruence</td>
<td>3.36 1.51 3.50 1.50</td>
<td>3.80 1.44 3.75 1.23</td>
<td>4.22 1.35 4.38 1.21</td>
<td>3.50 1.40 3.40 1.29</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Activation to the superior temporal gyrus (BA 22 x = 60, y = −39, z = 15; Figure 3D).

**DISCUSSION**

The present experiments produced some main findings, and here we report the principal results for Experiments 1 and 2.

In the first significant effect of Experiment 1 was related to the frontal cortical contribution to the processing of an anomalous action representation. Specifically, object-related actions that did not adequately correspond to the associated requirements for an action (being anomalously used) evoked a significant negative deflection (N400) within the frontal area. On the basis of the localization data, the prefrontal site (medial frontal gyrus) was responsible for incongruence processing, as revealed by the presence of a more anteriorly distributed N400 effect. This area could support semantic anomaly representation for an object-related action inserted into sequential frames. This increased N400 effect for incongruent conditions was found in previous studies (Balconi & Caldiroli, 2011; Proverbio et al., 2010; Sitnikova et al., 2008). In another study, the DLPFC was found to be responsive to action semantic anomalies tested by brain oscillations (Balconi & Vitaloni, 2012). However, the present research introduced an innovative approach by directly exploring the effect of tDCS on the DLPFC within a specific time interval: the 300–450 msec successive to the anomaly presentation. This study differed from previous studies that used a brain oscillation approach (Balconi & Vitaloni, 2012). Indeed, this methodological option allowed for us to verify the direct relationship between action and language semantic anomaly processing, considering the well-known effect of N400. In fact, not only did we find that a typical linguistic ERP deflection (the N400) was present in case of semantic action anomaly perception, but we also found that it was mainly frontally distributed (Experiment 1), inducing a significant distinction between the comprehension of the action and linguistic anomaly (Experiment 2, see also the following paragraph for the discussion of this point).

These results allowed for us to extend the assumption of a generic frontal cortical generator for semantic action representation (as shown in previous experiments, Balconi & Vitaloni, 2012) to a specific context, when the action was analyzed as a “linguistic phenomenon” by focusing on a “linguistic” ERP effect. That is, in the present experiment, we directly verified the effect induced by the incongruous condition for both action and language representation. Whereas previous results tested the brain correlates of anomaly processing in the action condition, in this study, we explored the specific different cortical generators supporting action and language comprehension, respectively. In general, we may state that, when examining the increased demand of incongruent semantic relationships in the neurocognitive process, mapping the action on a semantic memory network could modulate the N400 effect. Thus, we may conclude that the N400 effect was evoked by the presence of inappropriate information in an action representation when goal-related requirements of the actions (violation of instrumental requirements and incorrect use of an object) were disregarded.

Moreover, as suggested by LORETA, this effect was localized to the frontal area. These results confirmed what was found in previous research (Balconi & Vitaloni, 2012) for actions, and they provide evidence that the pFC area was systematically involved in the detection of anomalies in action representation within a semantic context. Because of this anterior distribution of the N400 deflection in cases of action representation, tDCS stimulation may have exerted a significant effect where the peak deflection was observed. This mechanism involves a more anterior distribution than the classical brain activation induced by generic linguistic anomalies, where a more posterior distribution has been revealed (Balconi & Pozzoli, 2004; Friederici et al., 2003). As found in previous studies that compared linguistic tasks, objects, actions, or scene materials, an anteriorly localized cortical network might directly respond to an action representation.
More generally, neuroimaging analyses performed during comprehension, exposure to visual images, or action execution implicate a broad network of cortical regions in the processing of common semantic relationships. It was found that stimuli that cannot be mapped on the semantic memory networks accessed by the preceding context evoke an increased response within the left inferior prefrontal and temporal cortices (Friederici et al., 2003). Some ERP analyses have shown that once object-action-specific memory representations within a specific context are activated, they influence the processing of incoming information related to the functionality of the object associated with that action by revealing an unusual, incongruent (or usual, congruent) representation (Proverbio et al., 2010; Sitnikova et al., 2008; Ganis & Kutas, 2003). Although in some cases, methodological approaches may differ (e.g., involving different reference sites, including mastoid, linked ears or common average references), with significant effects on the exact localization of the N400 component, we can conclude that instrumental incongruence occurred when the function of the object was not suitable to achieve the given action outcome supported by a frontal network.

The second main finding of this study was that partial inhibition of the frontal cortical region by tDCS reduced the standard “semantic incongruence effect,” as indicated by the decreasing N400 amplitude and some behavioral measures. Whereas in the absence of stimulation (sham conditions), a significant frontal increase in the N400 component was found for incongruent compared with congruent conditions, this effect was not observed in the case of stimulation (tDCS). The reduction of the N400 component in this frontal area in the case of tDCS inhibition may suggest a relevant role of the prefrontal area in this semantic process. In fact, the decrease in the N400 amplitude may be related to a subjective partial inability to process the semantic anomaly induced by an incongruent action as a consequence of the temporary inhibition of the left DLPFC.

Regarding the behavioral measures, as shown by the present results, when this semantic process is “inhibited” because of tDCS, participants appear to respond more randomly, showing increased ERs and reduced RTs. In other words, although incongruent conditions generally evoke longer RTs related to the increased cognitive effort required to process incoherent and incongruous information, in the present experiment, when the semantic processing of an anomaly was partially inhibited, participants showed a generally worse performance (increased ERs and decreased time to respond) that may highlight a more casual response behavior.

More generally, the prefrontal structures may be related to the process of error monitoring and checking for incongruent patterns. Specifically, visual action sequence comprehension may be supported by this cortical area and, in the case of DLPFC inhibition, the underlying mechanism may be partially impaired. Thus, a functional specificity of the prefrontal area for incongruence processing was suggested in cases of anomalous object use (Balconi & Vitaloni, 2012; Balconi & Caldiroli, 2011). However, as revealed by LORETA, a more medial area (the medial prefrontal gyrus) may be indicated as the specific brain correlate of incongruence processing for actions. This medial component may be related to the action representation when a violation is revealed. It was also shown that the left DLPFC was activated when participants decided whether two objects fit the requirements of a given action (Bach et al., 2010) or when stimuli could not be mapped on the semantic memory networks accessed by the preceding context (Friederici et al., 2003). Thus, more generally, the incongruence detection was a main specificity of DLPFC, mainly in cases of visual action patterns. However, future research should better explain the role of this medial brain area of pFC in comparison with other, more superficial PF correlates.

Experiment 2 highlighted some important findings, and it allowed us to confirm the presence of significant differences compared with Experiment 1. Specifically, the relevant role of cortical areas other than the DLPFC in processing linguistic semantic anomalies was confirmed in this experiment. Indeed, a specific activation of this cortical area (mainly BA 22, LORETA analysis) was found in response to the incongruent condition more than the congruent. Thus, a greater role of posterior sites than anterior sites in semantic processing was indicated. This posterior contribution was explainable considering the specific semantic conditions that we included in the present research, that is, a linguistic representation task. As shown by previous research, the semantic processing of linguistic anomalies may be supported by temporoparietal sites for incongruent representations (West & Holcomb, 2002; Barrett & Rugg, 1990), whereas object images or action-specific semantic processing may be more directly supported by anterior areas. Thus, these two visually and verbally guided processes showed their partial autonomy in terms of cortical generators, as shown in a previous study that demonstrated the independent ERP effect as a function of the type of stimulus (Landau, Aziz-Zadeh, & Ivry, 2010).

In support of these results, an N400 effect was revealed, with an increased peak amplitude being detected in response to incongruent representations within the temporoparietal area. The fact that a more posterior area was implicated in producing the N400 effect in cases of verbal action stimuli is in line with previous results: because N400 for verbal stimuli is generally more posteriorly produced, as reported in the literature, the main cortical localization of N400 was not frontal but temporoparietal. Moreover, because the tDCS stimulation was on the DLPFC and the cortical generators of N400 were localized on the superior temporal gyrus, no effect was observed by tDCS applied on the left DLPFC.
In summary, the results related to the representation of the semantic action-related and linguistic-related processing indicated different cortical ERP localizations and behavioral profiles. Thus, only object-related actions represented by visual frames were modulated by DLPFC inhibition, because this cortical correlation appears to allow the detection of semantic incongruence related to a specific task. On the contrary, linguistic anomalies appear to be supported by different cortical correlates that are more posteriorly localized. Taken together, these results underlined that the DLPFC is less relevant in processing semantic anomalies induced by a linguistic task, whereas it is relevant in processing semantic anomalies induced by a visual task. Thus, although we found significant similarities between action and language representation, as shown by the presence of two analogous N400 effects, their morphological resemblance and their similarity in the time onset, important differences were related to the cortical generators of the two ERP deflections. This important result was found for the first time by directly comparing a linguistic N400 ERP effect across action and language domains.

Thus, the pFC area should be considered as a specific cortical network that is deputed to process the action representation, mainly in cases of visual action processing rather than verbal action processing. Indeed, as suggested by previous research, the comprehension of verbal stimuli comprehension requires an ampler cortical network that includes temporal areas, whereas the prefrontal structures appear to be more directly finalized to process visual action displays, especially in cases of unattended and incoherent patterns. Thus, as shown by behavioral and ERP measurements, DLPFC stimulation may be not so relevant to induce a significant effect in verbal action processing, and other important cortical structures should be implicated in that case. However, the presence of different effects does not support an absolute independence of the cortical generators related to visual and verbal action representation, but it suggests the absence of a perfect correspondence and between the two cortical modules supporting visual and verbal stimuli.

**GENERAL DISCUSSION**

In the present research, we found that a specific frontal cortical site supports the semantic processing of observations of incongruent actions, and the left DLPFC was inferred to contribute to the comprehension of these semantic anomalies. As revealed by LORETA, the incongruent conditions elicited increased PF activation (mainly the medial prefrontal gyrus) in comparison with congruent conditions associated with visual frame comprehension (Experiment 1). In confirmation of this finding, the second main result revealed by this study was that the inhibition of the left DLPFC induced by tDCS may modulate the “incongruence effect,” as indicated by a decreased N400 peak amplitude, increased ERs, and decreased RTs. The general performance by the participants allowed us to suppose that more “random” behavior was induced by prefrontal inhibition. These results were compared directly with those of Experiment 2 to verify the specific effect of the left DLPFC on the processing of an action induced by verbal frames. A more posterior area (the superior temporal gyrus) was activated in response to an incongruent semantic representation induced by linguistic tasks. In this case, DLPFC inhibition did not result in a reduction of the incongruence effect. Thus, it was shown that the role of the DLPFC was specific to visual object-related action representations, and it was dependent on the task. The object-related action comprehension that occurred in the case of visual frames was partially impaired when the DLPFC was inhibited, as revealed by the decreased N400 component and increased ER.

More generally, regarding ERP correlates, we may conclude that the N400 semantic marker could help explain the relationship between action representation and cortical activation because different neurocognitive correlates that mediate the semantic representation of stimuli may be observed during the comprehension of action sequences and sentences. It could be argued that the N400 effect observed using a visual frame paradigm was differentially localized compared with the N400 component that was generally evoked by linguistic stimuli and that this ERP deflection was commonly increased when associated with incoherent actions. However, the more prefrontal anterior effect that was found on N400 ERPs in the case of visual action representation does not indicate an “exclusive” DLPFC contribution to visual action processing, but, as shown by the LORETA source localization paradigm, that the medial frontal gyrus may be specifically indicated as the principal cortical area where the tDCS induced the most significant modifications in N400 amplitude. Therefore, to elicit a complete overview of the cortical localization effect induced by tDCS on the prefrontal area, other ERP and neuroimaging measures should be amply tested.

Another consideration concerns the direct effects of brain stimulation techniques such as tDCS on the EEG/behavioral profile. The observed differences in these measures between pre- and poststimulation may furnish important details regarding the impact of the cortical neuromodulation induced by tDCS on participants’ performance. Indeed, we tested for changes in the ER, RT, and ERP cortical responses induced by direct current stimulation. Moreover, the effect of tDCS was investigated to examine the modulation of the ERP/behavior associated with incongruent conditions in comparison with the absence of stimulation (sham effect). On the basis of these experiments, we may conclude that the investigation of behavioral and electrophysiological correlates underlying the effects of tDCS on the semantic comprehension of actions is necessary and useful. Specifically, the present...
research contributed to the documentation of the EEG changes induced by tDCS applied over the frontal cortex when a semantic task is performed.

However, future studies may contribute to better describing the cortical correlates of observing action, taking into account other important frontal areas that were found to support semantic processing. Second, the contribution of the more dorsal and medial parts of pFC in inducing this “inhibition” effect should be explored in the future using adjunctive neuroimaging measures that are able to distinguish different areas’ contribution and the tDCS effect. This suggestion is also related to the nature of tDCS stimulation and its “extended” effect on the scalp surface. Third, it is suggested that the present data should be integrated with data obtained by applying tDCS to the right DLPFC to better explain the possible lateralization effect found in this study. Moreover, anodal effects could be considered by inducing an “activation effect” on the DLPFC and successively comparing this effect with that found in the present research. Finally, future research may improve the analysis of the effects of tDCS on EEG/ERP measures by also considering the direct relationship between this neurostimulation technique and brain oscillatory activity. This comparison could contribute important considerations about the tDCS effect on both the ERP and brain oscillation variables, showing the main similarities and differences induced by neuromodulation on these distinct phenomena (cortical band and ERP peak deflection analysis). On the other hand, as some authors considered the EEG oscillations to be usable predictors for ERP effects, a specific comparison between the two phenomena could contribute to the exploration of their intrinsic relationship.

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