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Electrifying discourse: Anodal tDCS of the primary motor cortex selectively reduces action appraisal in naturalistic narratives

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Abstract

Non-invasive stimulation of the primary motor cortex (M1) modulates processing of decontextualized action words and sentences (i.e., verbal units denoting bodily motion). This suggests that language comprehension hinges on brain circuits mediating the bodily experiences evoked by verbal material. Yet, despite its relevance to constrain mechanistic language models, such a finding fails to reveal whether and how relevant circuits operate in the face of full-blown,

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Data and code availability statement

All experimental data, as well as the scripts used for their collection and analysis, are fully available online (García, 2020).

Open practices

The study in this article earned Open Materials and Open Data badges for transparent practices. Materials and data for the study are available at https://osf.io/yge6s/?view_only=00ea7706d75e43c288aeabdb9b477e63.

Declaration of competing interest

The authors declare no competing financial interests.

everyday texts. Using a novel naturalistic discourse paradigm, we examined whether direct modulation of M1 excitability influences the appraisal of narrated actions. Following random group assignment, participants received anodal transcranial direct current stimulation over the left M1, or sham stimulation of the same area, or anodal stimulation of the left ventrolateral prefrontal cortex. Immediately afterwards, they listened to action-laden and neutral stories and answered questions on information realized by verbs (denoting action and non-action processes) and circumstances (conveying locative or temporal details). Anodal stimulation of the left M1 selectively decreased outcomes on action-relative to non-action information –a pattern that discriminated between stimulated and sham participants with 74% accuracy. This result was particular to M1 and held irrespective of the subjects' working memory and vocabulary skills, further attesting to its specificity. Our findings suggest that offline modulation of motor-network excitability might lead to transient unavailability of putative resources needed to evoke actions in naturalistic texts, opening promising avenues for the language embodiment framework.

Keywords

Action semantics; Embodied cognition; Ecological validity; Naturalistic text processing; Transcranial direct current; stimulation

1. Introduction

Within the growing literature on non-invasive brain stimulation (NIBS) (Bachtar et al., 2018; Fregni & Pascual-Leone, 2007), accruing evidence shows that modulation of the primary motor cortex (M1) significantly affects the processing of motoric action verbs or sentences-linguistic units denoting bodily movements (D'Ausilio et al., 2009; Liuzzi et al., 2010; Papeo et al., 2009; Willems et al., 2011). Such evidence supports the view that language comprehension is partially embodied, that is, critically subserved by circuits mediating the bodily experiences evoked by verbal material (García et al., 2019, 2020; Pulvermüller, 2013, 2018). However, all relevant studies so far have employed isolated, decontextualized stimuli, thus failing to tap into the mechanisms engaged by *naturalistic discourse*. This issue underpins an emergent neuroscientific framework seeking to bridge the gap between laboratory designs and embodied semantics under ecological conditions (Desai et al., 2016; García et al., 2016, 2018; Hasson et al., 2018; Trevisan et al., 2017). Working in this direction, we used anodal transcranial direct current stimulation (tDCS) to explore how modulation of M1 excitability affects the processing of actions in naturalistic narratives.

Depending on task-related, stimulus-specific, and device-setting parameters, stimulation of motor regions can either improve (Pulvermüller et al., 2005; Tomasino et al., 2008; Vicario & Rumiati, 2012; Willems et al., 2011) or worsen (Branscheidt et al., 2017; Kuipers et al., 2013; Liuzzi et al., 2010; Papeo et al., 2009; Vukovic et al., 2017) processing of single action words and sentences. The latter pattern, in particular, may hold major theoretical relevance, as evidence of action-semantic *disruptions* following motor-region modulation represents a milestone to demonstrate a direct role of embodied circuits in language function (Vukovic et al., 2017). Although the mechanisms leading to such disturbances remain unclear (Pulvermüller, 2018), a partial yet plausible explanation can be found in the Hand-

Action-Network Dynamic Language Embodiment (HANDLE) model (García & Ibáñez, 2016b). This framework posits that if motor circuits are in a supra-threshold (hyper-excited) state during action-language processing, behavioral outcomes will be reduced because critical embodied resources will not be optimally available for task completion. For example, as shown in varied paradigms, processing of action verbs can delay the planning and/or execution of effector-congruent movements, suggesting reduced accessibility to shared embodied resources (Buccino et al., 2005; de Vega et al., 2013; García & Ibáñez, 2016a; Glenberg et al., 2008). By the same token, if the embodied mechanisms operative in the face of decontextualized verbal materials are similarly at play in naturalistic language tasks, then comparable effects should be observed in context-rich narratives (García et al., 2018).

This hypothesis can be directly tested via anodal tDCS, a technique that can modulate cortical excitability of the targeted region (Nitsche & Paulus, 2000). Crucially, although anodal stimulation of M1 can improve motor learning if applied during task execution (Nitsche et al., 2003; Ziemann & Siebner, 2008), the same process becomes impaired if such an intervention occurs *before* the task (Amadi et al., 2015; Apsvalka et al., 2018; Stagg et al., 2011) –as also observed for visuomotor learning (Leow et al., 2014). This is also true in the language domain. Indeed, *offline* application of this very method to motor regions can selectively disrupt action-verb access (Gijssels et al., 2018). To date, however, no study has explored whether these outcomes emerge in the face of ecological texts, casting doubts on their relevance for understanding real-life language processing. As it happens, the effects reported in single-word and single-sentence tasks cannot be a priori assumed to be present when dealing with discourse-level materials, given that contextual information modulates action-word processing (García & Ibáñez, 2016b; Van Dam et al., 2010) and facilitates linguistic performance by favoring maintenance of relevant information (Ledoux et al., 2006). A direct examination of this issue, therefore, can address recent calls for more ecological assessments within the language embodiment framework (Birba et al., 2020; Desai et al., 2016; García et al., 2018; Trevisan et al., 2017).

Building on the HANDLE model and the findings above, we hypothesized that modulation of motor cortex excitability via anodal tDCS would trigger selective difficulties for action information in naturalistic narratives. We employed a validated paradigm (García et al., 2018; Trevisan et al., 2017) capturing action appraisal –i.e., a cross-dimensional ecological process integrating lexical, syntactic, semantic, pragmatic, and no less importantly, memory demands. To test our conjecture, we manipulated three key factors, namely: Group, Text type, and Information type. Specifically, we applied anodal or sham tDCS over the left M1 region of healthy subjects (Group); presented them with action-laden and neutral narratives (Text type); and had them answer questions on the characters' motoric actions, their non-motoric (e.g., mental, sensory) activities, and the locative or temporal circumstances of those events (Information type). Therefore, we predicted a significant triple interaction between the three factors, such that action comprehension (in the action-laden narratives) would be selectively reduced for the group undergoing anodal M1 stimulation. In addition, to test the regional specificity of the predicted M1 effect, we included a third group undergoing anodal tDCS on the left ventrolateral prefrontal cortex (VLPFC), a region implicated in working memory (WM) (Badre & Wagner, 2007) and processing of multiple verb categories (Vigliocco et al., 2011). Moreover, we employed machine-learning and covariance analyses

to establish the potential robustness and primary nature of the predicted M1 effect across individual subjects. Briefly, our study aims to nurture the ongoing debate (Caramazza et al., 2014; de Zubicaray et al., 2013; Hickok et al., 2011; Papeo et al., 2013) on whether motor system activity plays a primary role in grounding action semantics, while inaugurating promising ecological avenues for the embodied cognition framework at large.

2. Methods

In line with current transparency standards, we report how we determined our sample size, all data exclusions (if any), all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

2.1. Participants

To determine the sample size required for our cross-textual analysis, we ran a power estimation on R with the pwr library ($p = .05$; $\eta^2 = .52$; power = .8). This analysis showed that a sample size of 12 is enough to reach the estimated effects of García et al. (2018). The study included 68 native Spanish-speaking volunteers. All participants were right-handed, possessed normal or corrected-to-normal vision, presented no history of psychiatric or neurological disease, and had no contraindications for undergoing tDCS or transcranial magnetic stimulation (TMS), as confirmed through a standardized questionnaire. Participants were randomly assigned to one of three experimental groups: anodal-M1, sham-M1 or anodal-VLPFC. Six participants were excluded from the study because they failed to complete all sessions in the protocol. The final sample ($n = 62$) consisted of 19 subjects (15 female) for the anodal-M1 group, 23 (16 female) for the sham-M1 group, and 20 (17 females) for the anodal-VLPFC group, and reaches a power of .99. All groups were matched in terms of sex ($X^2 = 2.60$, $p = .27$), age [anodal-M1: $M = 21.15$, $SD = 1.22$; sham-M1: $M = 23.43$, $SD = 1.11$; anodal-VLPFC: $M = 23.5$, $SD = 4.35$; $F(1,59) = 1.56$, $p = .21$], and education [anodal-M1: $M = 14.47$, $SD = .75$; sham-M1: $M = 16.21$, $SD = .68$; anodal-VLPFC: $M = 15.8$, $SD = 2.23$; $F(1,59) = 1.7$, $p = .19$].

All participants read and signed an informed consent form before beginning the study. The protocol was carried out in accordance with the principles of the Declaration of Helsinki and was approved by the Ethical Research Committees of the University of La Laguna (Spain) and the Institute of Cognitive Neurology (Argentina). No part of the study procedures or analyses was pre-registered prior to the research being conducted.

2.2. Materials

2.2.1. Naturalistic narrative task

2.2.1.1. NARRATIVES.: The two naturalistic stories composed by García et al. (2018) were adapted to the local dialect and complemented by two additional stories. Two of the narratives, dubbed ‘action texts’ (ATs), systematically focused on the characters’ bodily movements, whereas the other two, called ‘neutral texts’ (NTs), were characterized by low action content.

The ATs consisted in action-laden stories that described multiple bodily movements of their characters, including physical interactions with people and objects (as illustrated by this passage: “*Juancito ran quickly to the place where the clown was jumping and dancing*”). Also, the texts offered rich details about the settings where the stories took place, the objects in them, and the manner in which bodily actions were performed. On the other hand, the NTs mainly described non-action events, such as the feelings, thoughts, and perceptions of their characters, with several sentences focused on their inner states (as in this excerpt: “*Alberto heard his favorite song and felt uplifted*”). Also, the texts offered abundant circumstantial information depicting places, objects, and temporal features of the characters’ emotions or other internal states.

The four narratives were constructed in Spanish following a strictly controlled protocol (Trevisan & García, 2019), reported in previous works (García et al., 2018; Trevisan et al., 2017). Specifically, all texts were constructed on the basis of 22 pseudo-randomly distributed grammatical patterns and filled with selected lexical items. Each text included 32 verbs which satisfied non-action versus action opposition, following formal semantic, syntactic, and distributional criteria (Halliday et al., 2014). Minor adjustments to the ensuing sentences were then applied to enhance cohesion and coherence in each text. In addition, the texts were matched for (i) character count; (ii) overall and content-word-type counts; (iii) mean content-word frequency, familiarity, syllabic length, number of letters, and imageability; (iv) sentence and sentence-type counts; (v) reading difficulty; and (vi) readability ratings. Moreover, ratings from a panel of 31 Spanish-speaking readers showed that the texts were similar in terms of overall emotional content (positive, negative or neutral) and arousal level (intensity of the chosen emotion from 1 to 7) –all texts were rated as emotionally positive. Furthermore, the specific verbs targeted by each verb-related question in the questionnaires were matched for frequency, familiarity, syllabic length, number of letters, and imageability. See Table 1 for statistical details.

The texts were audio-recorded by a male native speaker of Canary Spanish, the participants’ native dialect. A smooth narration pace was used in all cases. The files were recorded in.mp3 format with stereo output, and each of them lasted roughly 100 sec (all audio files and their scripts are available upon request). Importantly, analyses performed with Neuro-speech software® (Orozco-Arroyave et al., 2018) confirmed that all four narratives were comparable across key prosodic variables, namely: voiced segments, silence segments, average fundamental frequency, and average energy (Cutler et al., 1997; Noth et al., 2000) (Table 1).

2.2.1.2. Questionnaires.: For each text, we designed a 20-item multiple-choice questionnaire, comprised entirely of wh-questions. In each questionnaire, half the questions ($n = 10$) pointed to verb-related information. The other half ($n = 10$) aimed at circumstances, realized by adverbial or prepositional phrases pointing to locative, causal, temporal, or modal information. All verb-related questions in the AT questionnaires referred to action verbs, and those in the NT questionnaires pointed to non-action verbs. Importantly, the inclusion of both types of question allowed exploring potential dissociations between the comprehension action (verb-related) information and non-action (circumstantial) information in the AT.

Questions were presented following the order of the corresponding events in the texts, with alternation between verb-related and circumstantial items. While previous versions of this paradigm were aimed at pathological populations (García et al., 2018; Trevisan et al., 2017) and minimized memory demands, here we employed more challenging questionnaires for healthy participants, with all options in each question evoking very similar meanings. Specifically, each question was accompanied by five options: one correct option, three subtly incorrect options, and an ‘I don’t remember’ option. Sequencing of the options was randomized, except for the ‘I don’t remember’ option, which was always presented last. Correct responses were given one point, while incorrect answers or the ‘I don’t remember’ option were given zero points. Therefore, each questionnaire had a maximum score of 20 points (10 for verb-related questions and 10 for questions about circumstantial information). Given that our paradigm included two texts of each type, each condition had a maximum score of 20 points.

2.2.2. Complementary assessments—To examine the potential impact of general mnemonic and linguistic skills on text appraisal results, we administered a WM task (Rodrigo et al., 2014) and the Peabody Picture Vocabulary Test III (PPVT-III) (Dunn & Dunn, 1997). This evaluation was performed when subjects were not under the influence of stimulation (Kaski et al., 2014), and it allowed ruling out potential coarse-grained cognitive differences between-groups.

2.2.2.1. Working memory.: Auditory verbal WM was assessed via the Spanish adaptation of a validated listening span test (Rodrigo et al., 2014). Participants were required to supply the missing final words of unrelated sentences and to recall all the supplied words at the end of the set. The missing words were concrete disyllabic nouns [e.g., “*In summer it is very_____*” (“*En verano hace mucho_____*”). The participant was then required to repeat the words that he or she had selected –in this case, *hot (calor)*. The task increased the number of items in each level, starting with two and leading to five items. Task administration was stopped when the participant failed all items at a given level. Correct and incorrect answers were given one and zero points, respectively. The maximum score was 42.

2.2.2.2. Receptive vocabulary.: Receptive vocabulary knowledge was measured with the validated Spanish version of the PPVT-III (Dunn & Dunn, 1997). This instrument, which has a test-retest reliability of .93 and an internal consistency score ranging between .89 and .97, has been successfully used to establish vocabulary skills in healthy young adults (Kemper & Sumner, 2001). The test consists of 16 levels with 12 trials featuring four pictures each. In each case, the examiner uttered a word and participants had to select which of the pictures matched its meaning. Correct responses were given one point and incorrect ones received zero points. The score was calculated as the number of the highest trial reached minus the number of errors committed. The maximum score was 192.

2.3. Experimental session

The study consisted of two successive sessions. First, participants completed the experimental session, which comprised an offline stimulation phase and a behavioral testing

phase. Second, they performed the complementary WM and vocabulary assessments. The structure of the experimental session is diagrammed in Fig. 1.

2.3.1. Offline stimulation phase—To stimulate M1, we first identified the ‘hand motor hotspot’ with single-pulse TMS and then applied tDCS to this area. Given the non-focal nature of tDCS, this approach allowed us to modulate activity across large portions of the M1 region. For the anodal-M1 and the sham-M1 groups, participants sat on a comfortable chair with head- and arm-rests, and the ‘motor hotspot’ was identified through single-pulse TMS, applied via a Magstim 200 magnetic stimulator (Magstim, Whiteland, Dyfed, UK) with a figure-of-eight magnetic coil (diameter of 1 winding = 70 mm). The coil was held tangentially to the skull, with the handle pointing backward and laterally at an angle of 45° from the midline. Surface electromyogram was recorded from the right FDI with Ag–AgCl electrodes in a belly-tendon montage (Moliadze et al., 2010). The ‘motor hotspot’ was localized as the optimal scalp position at which TMS evoked a just-noticeable twitch from the relaxed contralateral FDI muscle (Nitsche & Paulus, 2000).

Then, using a DC-Stimulator (Eldith, Germany), and following reported procedures (Wiethoff et al., 2014), we applied tDCS at 2 mA for 20 min in the anodal-M1 and anodal-VLPFC groups and for 30 sec in the sham-M1 group. At the onset of stimulation, for all three groups, the current was increased in a ramp-like fashion over 8 sec, and at the end it was slowly decreased for another 8 sec, until it turned off—a procedure demonstrated to warrant successful blinding (Gandiga et al., 2006). Stimulation was delivered through two sponge electrodes (Eldith, Germany) embedded in a saline-soaked solution. For the anodal-M1 and sham-M1 groups, the stimulating electrode (surface area 25 cm²) was then positioned over the left-hemispheric motor hotspot of the hand M1 region, and the reference electrode (surface area 35 cm²) was placed on the skin overlying the right supraorbital region (Nitsche et al., 2007). By contrast, and in line with previous VLPFC stimulation protocols (Chrysikou et al., 2013; Medvedeva et al., 2018), the anode for the anodal-VLPFC group was placed over site F7 according to the 10–20 EEG system. The reference electrode was placed over the right supraorbital region—as done for the anodal-M1 and sham-M1 groups. Overall, the offline stimulation phase lasted 20 min.

2.3.2. Behavioral testing phase—After the offline stimulation phase, participants were instructed to close their eyes and listen carefully to the recorded texts through professional, high-definition headphones. The participants were introduced to and familiarized with the task through a brief practice block, which consisted in one narrative with the same length and structure as the ones in the experiment, followed by three sample questions. After the practice, participants listened to the two ATs and the two NTs. Each text was played only once. ATs and NTs were systematically alternated and counterbalanced across participants (texts from the same category were never presented successively). Immediately after each text, the volunteer was presented with the corresponding 20 questions on a computer screen and asked to choose the correct answer as quickly as possible, using predefined keys from a numeric pad. Selected options were automatically saved.

2.3.3. Complementary assessment phase—The complementary tasks were administered on a different day by one of the researchers (AB or IPG) in a quiet room with dim lights. All subjects performed the WM task first, followed by the PPVT-III.

2.4. Data analysis

Performance on the naturalistic narrative task was analyzed via a mixed-model ANOVA, with one between-subject factor (Group: anodal-M1, sham-M1, anodal-VLPFC) and two within-subject factors (Text type: AT, NT; Information type: circumstantial, verb-related). Also, we performed subtraction analyses to examine action-verb differences between groups while controlling for overall verb-related outcomes. Specifically, for each participant, we subtracted the AT scores in each category from the corresponding NT scores, namely: action verbs in ATs minus non-action verbs in NTs, and circumstances in ATs minus circumstances in NTs. Hence, these analyses capture performance on our target category (AT verbs) relative to their category-specific control condition (NT verbs) –a useful and informative approach given that frontal regions underlie processing of verbs in general (Vigliocco et al., 2011). The ensuing results were analyzed via a mixed-model ANOVA with a between-subject factor (Group: anodal-M1, sham-M1, anodal-VLPFC) and a within-subject factor (Information type: verb-related, circumstantial). Interaction effects analyses were scrutinized via Tukey's HSD post-hoc tests. Alpha levels were set at $p < .05$. Effect sizes were calculated through partial eta squared (η^2) tests for ANOVA results and Cohen's d for pairwise comparisons. These analyses were performed on R 3.5.2 (Team, 2018).

Furthermore, in line with recent approaches to embodiment research (García et al., 2019, 2020), the abovementioned ANOVAs were complemented with machine learning analyses. While the former capture aggregate effects across all subjects within the compared groups, the latter reveals how consistent the effects prove at the single-subject level. To this end, we implemented an SVM, namely, a binary classifier capable of finding the best hyperplane separating data variables according their class (Noble, 2006). The algorithm involved a training stage and a testing stage. In the training stage, a subset of the data (belonging to 31 randomly selected subjects for anodal- and sham-M1; 32 for sham-M1 and anodal-VLPFC; and 29 for anodal-M1 and anodal-VLPFC) and their corresponding classes (sham-M1, anodal-M1, and anodal-VLPFC) were used to determine the classification parameters (Núñez et al., 2002). Then, in the testing stage, the rest of the data were segregated as one of the two possible classes. This procedure was repeated 1,000 times, randomly dividing the training and testing subsets, and yielded mean accuracy with its corresponding standard deviations (Dottori et al., 2017). To examine the effect of the stimulation in action-verbs and control for overall verb-related outcomes, we performed the classification analyses considering the subtraction scores for each information type (verbs and circumstantial). This allowed us to determine the best indexes classifying group subjects for anodal-M1 versus sham-M1, sham-M1 versus anodal-VLPFC, and anodal-M1 versus anodal-VLPFC. The analyses were performed with the default SVM function of MATLAB software®.

Moreover, we conducted receiver-operating characteristic (ROC) curve analyses to illustrate the results of the SVM classification. The areas under the ROC curves were compared via the method proposed by DeLong et al. (1988). To this end, we used a MATLAB script

including the implementation of DeLong's algorithm –proposed by Sun and Xu (2014)–, as well as the parametric test proposed by Hanley and McNeil (1982). All these analyses were performed on MATLAB software®.

In addition, results from the WM task and the PPVT-III were compared among groups through two-tailed one-way ANOVAs. Finally, to determine whether potential text retrieval outcomes were related to WM and vocabulary skills, we reanalyzed the results from the naturalistic narrative task using the total WM and PPVT-III scores as covariates. All these analyses were also performed on R 3.5.2 (Team, 2018).

3. Results

3.1. Outcomes from the naturalistic text task

All subjects had at least above 55% of correct responses in three out of four conditions (verb-related information in the AT, verb-related information in the NT, circumstantial information in the AT, circumstantial information in the NT). Analysis of both text types revealed a triple interaction among Group, Text type, and Information type [$F(2,59) = 5.02$, $p < .01$, $\eta^2 = .02$]. Post-hoc comparisons, via Tukey's HSD tests ($MSE = 8.75$, $df = 93.03$), revealed a significant selective effect in the anodal-M1 group, characterized by lower performance on verb-related questions in the AT (action verbs) compared to both circumstantial questions in the same text ($p = .02$, $d = .90$) and verb-related questions in the NT (non-action verbs) ($p = .001$, $d = 1.33$) (Fig. 2A, middle inset). Differences in all other comparisons in this group were non-significant (all p -values $> .20$) (Fig. 2A, middle inset). Also, no significant differences emerged in the sham-M1 group between ATs and NTs, for either verb-related or circumstantial information (Fig. 2A, left inset), indicating similar performance on all conditions (all p -values $> .75$). Additionally, results from the anodal-VLPFC group showed no significant intra-group differences between ATs and NTs for Information type, corroborating the regional specificity of the action-verbs decrement following anodal M1 stimulation (Fig. 2A, right inset). Furthermore, the anodal-VLPFC group showed increased performance on non-action verbs compared to the sham-M1 group ($p < .01$, $d = .26$), alongside better performance on action verbs relative to the anodal-M1 group ($p = .03$, $d = 1.05$) –Fig. 2A. All other pairwise comparisons within and between groups were non-significant (all p -values $> .77$).

Such a selective effect was corroborated upon subtracting the outcomes on each Information type (verb-related and circumstantial) between texts. This analysis revealed a significant interaction between Information type and Group [$F(2, 59) = 5.02$, $p < .01$, $\eta^2 = .07$]. A post-hoc analysis, via Tukey's HSD test ($MSE = 9.50$, $df = 116.78$), showed a significant decrement in verbs for the anodal-M1 group relative to sham-M1 group ($p = .003$, $d = 1.04$) (Fig. 2B, right inset), and no significant effect on circumstantial information (all p -values $> .50$, Fig. 2B, left inset).

3.2. SVM results

The subtraction of verb-related information between the AT and the NT robustly discriminated anodal-M1 participants from subjects in the sham-M1 group (classification

rate: $74\% \pm .02$, Fig. 2C, upper inset) and in the anodal-VLPFC group (classification rate: $70\% \pm .03$, Fig. 2C, middle inset). Classification for the anodal-VLPFC and sham-M1 groups yielded lower discriminatory accuracy (classification rate: $62\% \pm .04$; Fig. 2C, lower inset). The ROC curves of the subtraction of verb-related information between the AT and the NT illustrate the high classification rate obtained through these analyses (area under the curve for anodal-M1 vs sham-M1: .73 CI: .57–.89; $p = .01$; area under the curve for anodal-M1 vs anodal-VLPFC: .70 CI: .53–.87; $p = .02$; area under the curve for anodal-VLPFC vs sham-M1: .62 CI: .45–.80, $p = .16$).

On the other hand, the subtraction for circumstantial information did not yield good discrimination rates in any of the three SVM analyses (anodal-M1 vs sham-M1: $63\% \pm .03$; anodal-M1 vs anodal-VLPFC: $48\% \pm .06$; anodal-VLPFC vs sham-M1: $59\% \pm .02$), and the ROC curves were near the line of identity (area under the curve: anodal-M1 vs sham-M1: .58, CI: .41–.76; $p = .33$, anodal-M1 vs anodal-VLPFC: .50, CI: .31–.68; $p = .99$; sham-M1 vs anodal-VLPFC: .57, CI: .40–.75; $p = .38$). Also, a statistical comparison between the areas under the ROC curves revealed better discrimination accuracy for verb-related information compared to circumstantial information only for the anodal-M1 versus sham-M1 SVM analysis ($p = .002$). The other two contrasts did not present significant differences between curves (anodal-M1 vs anodal-VLPFC: $p = .12$; anodal-VLPFC vs sham-M1: $p = .09$) (Fig. 2, panel C, middle and lower insets).

3.3. Impact of WM skills and vocabulary knowledge

The three groups exhibited comparable performance on the WM task [$F(2, 51) = 2.090$, $p = .13$, $\eta^2 = .006$] and the receptive vocabulary (PPVT-III) test [$F(1, 51) = .351$, $p = .70$, $\eta^2 = .004$]. Notably, the main results remained significant after co-variation with these measures, suggesting that the effect of the anodal stimulation on action information was not explained by more general factors, such as overall memory skills or vocabulary knowledge.

Likewise, the significant decrement in the appraisal of verb-related information for ATs in the anodal-M1 group, signaled by the triple interaction described above, survived covariation with WM results [$F(2, 51) = 4.270$, $p = .015$, $\eta^2 = .02$]. Tukey's HSD (MSE = 8.74, $df = 79.60$) tests revealed that the effect in the anodal-M1 group remained selectively driven by reduced performance for action verbs relative to non-action verbs in the NT ($p = .007$, $d = 1.22$) and circumstances in the AT ($p = .041$, $d = .81$). Furthermore, increased performance on action verbs for the anodal-VLPFC relative to the anodal-M1 group also survived covariation with WM results ($p = .03$, $d = .97$). The critical triple interaction also remained significant upon covarying for PPVT-III results [$F(1, 51) = 4.27$, $p = .01$, $\eta^2 = .02$]. Once again, Tukey's HSD (MSE = 8.83, $df = 78.00$) tests showed that the appraisal of action verbs in the anodal-M1 group was significantly lower than that of non-action verbs in the NT ($p = .007$, $d = 1.22$), and circumstances in the AT ($p = .041$, $d = .81$). Furthermore, higher outcomes for action verbs for the anodal-VLPFC relative to the anodal-M1 group remained significant after covarying for PPVT-III results ($p = .03$, $d = .97$).

Finally, the selective effect observed in the anodal-M1 group in the subtraction analysis also remained significant when covarying for WM scores [$F(1, 51) = 3.78$, $p = .03$, $\eta^2 = .02$]. A post-hoc analysis, via Tukey's HSD (MSE = 9.68, $df = 98.82$) test, revealed a significant

decrement in action (minus non-action) verbs in the anodal-M1 group compared to the sham-M1 group ($p = .028$, $d = .88$). Likewise, this key effect survived covariation for vocabulary scores [$F(2,51) = 3.78$, $p = .02$, $\eta^2 = .02$]. Tukey's HSD test ($MSE = 9.52$, $df = 98.32$), once again, showed that the appraisal of action (minus non-action) verbs in the anodal-M1 group was lower than in the sham-M1 group ($p = .034$, $d = .88$). Neither of these analyses yielded significant between-group differences for circumstantial information (all p -values $> .05$).

4. Discussion

This is the first NIBS study to examine embodied mechanisms involved in text-level processing. Action appraisal was selectively reduced after 20 min of anodal tDCS over M1, with no differences after sham treatment and no action-specific effects following VLPFC stimulation. Moreover, performance on action-information, relative to non-action information, robustly classified subjects as having undergone anodal-M1 tDCS or not. Finally, these results were uninfluenced by individual variability in WM and vocabulary skills. Therefore, motor systems seem critically and selectively involved in retrieving actions evoked by naturalistic narratives.

Although anodal tDCS over M1 has been associated with improved action-related outcomes (Reis & Fritsch, 2011), the selective decrement observed is predictable given our protocol's temporal design. Motor-learning studies show that anodal M1 stimulation reduces reaction times when applied *during* the task (Nitsche et al., 2003; Ziemann & Siebner, 2008) but delays responses when applied *before* the task (Amadi et al., 2015; Apsvalka et al., 2018; Stagg et al., 2011). Likewise, *offline* application of anodal tDCS over motor circuits selectively disrupts access to action (compared to abstract) verbs during lexical decision (Gijssels et al., 2018) and yields lower mean outcomes in action-word learning paradigms (Branscheidt et al., 2017; Liuzzi et al., 2010). Compatibly, sustained motor system recruitment through manual-movement practice can *subsequently decrease* the comprehension of directionally compatible action sentences (Glenberg et al., 2008). Our study extends these findings, showing that offline application of anodal tDCS over M1 can selectively disrupt action-verb processing even in text-level materials.

This result can be straightforwardly interpreted in terms of the HANDLE model (García & Ibáñez, 2016b). HANDLE predicts that if motor circuits are in a supra-threshold (hyper-excited) state during action-language processing, behavioral outcomes will be reduced because critical embodied resources will not be optimally available for task completion. Suggestively, this explanation is consistent with the notion of homeostatic metaplasticity, which posits that prior excitation of a given circuit elevates its activation threshold and decreases its predisposition for further excitation (Hurley & Machado, 2017). Given that action-related meanings are grounded in motor circuits (Birba et al., 2017; Pulvermüller, 2018), modulation of M1 by anodal tDCS would yield precisely such supra-threshold states and selectively decrease access to modality-specific processes underlying action-language outcomes.

However, it may also be the case that the selective effect we observed was contingent on a different neuroplastic process. In fact, anodal tDCS over language-related areas (in particular, the left inferior frontal gyrus) has been shown to *decrease* regional activation, leading to improved lexico-semantic processing in word generation (Meinzer et al., 2012a, 2013) and picture naming (Holland et al., 2011) tasks. However, note that these studies differ from the present one in stimulation and task-related factors known to modulate neuromodulation outcomes (Galli et al., 2019): indeed, they employed online (rather than offline) stimulation and induced improvements (as opposed to disadvantages) over categorically unspecific (as opposed to modality-specific) verbal materials. Therefore, although our design does not rule out region-specific deactivations as the basis of the observed effect, the hyper-excitation account seems at least plausible given the experiment's stimulation parameters. This scenario, in any case, calls for new renditions of our study in combined tDCS-fMRI settings. Whereas the fine-grained neuroplastic mechanisms elicited by anodal tDCS remain poorly understood (Roche et al., 2015; Wiethoff et al., 2014), the detection of selective embodied effects via direct stimulation evidence holds important theoretical value. In line with previous tDCS works (Branscheidt et al., 2017; Gijssels et al., 2018; Liuzzi et al., 2010), present results show that artificially induced changes in M1 polarity can *trigger* category-specific effects. The direction of the outcomes reinforces this conclusion: whereas NIBS protocols showing enhanced results are sometimes undermined by task-learning or task-exposure confounds, evidence of *reduced* performance despite trial accumulation attests to the fundamental role of motor circuits for grounding modality-specific meanings (Vukovic et al., 2017). Therefore, our study offers crucial constraints to delineate mechanistic embodied theories.

More particularly, our central finding is that such direct effects are also operative in text-level processing. So far, all NIBS investigations of embodied language mechanisms have relied on isolated, randomly sequenced words or sentences (D'Ausilio et al., 2009; Gijssels et al., 2018; Liuzzi et al., 2010; Papeo et al., 2009; Willems et al., 2011). Despite their major contributions, such findings overlook the role of modality-specific mechanisms in naturalistic language processing. Furthermore, they cannot be a priori assumed to hold in the face of coherent and cohesive texts, characterized by multiple contextual constraints and increasingly complex semantic relations which unfold sentence after sentence (García et al., 2016). Against this background, and together with demonstrations that processing of actions in naturalistic texts can be selectively modulated by bodily training (Trevisan et al., 2017) and distinctively impaired following motor-network damage (García et al., 2018), our results indicate that embodied systems are non-trivially involved in the appraisal of semantic information from naturalistic texts.

Moreover, this selective effect was specific to M1, since, relative to the sham group, anodal-VLPFC subjects exhibited no effects on action-related information. In fact, the latter treatment boosted the appraisal of *non-action* processes. This finding aligns with fMRI and TMS studies showing that this prefrontal region, though not putatively related to action-verb processing (Pulvermüller, 2013, 2018), subserves the formation of memory traces across varied verbal categories (Galli et al., 2017). In particular, VLPFC activity has been linked to verbal WM (Veltman et al., 2003) and, more crucially, verb retrieval at large (Vigliocco et al., 2011). Furthermore, anodal tDCS over this region facilitates semantic fluency (Cattaneo

et al., 2011; Meinzer et al., 2012b) and picture naming (Sparing et al., 2008) across varied word classes. Thus, results from the anodal-VLPFC group could reflect the general involvement of this region in *transcategorical* verb information (including non-action verbs in general), attesting to the regional specificity of the action-selective effect observed after M1 stimulation. In this sense, the decrement in action-process outcomes could arguably reflect competition for shared fine-grained resources (cf. the HANDLE model), whereas the enhancement of non-action-process outcomes in the anodal-VLPFC group might reflect the coarser-grained relation between inferior frontal (extra-motor) regions and general processing of verbs holding no specific embodied relation to them (Vigliocco et al., 2011) – in which case there would be no competition for common fine-grained resources.

Also notable is the fact that, as shown by SVM analyses, results from the anodal-M1 group proved robust at an individual level. Whereas tDCS effects on other behavioral outcomes are highly variable and actually absent in roughly 50% of the population (Wiethoff et al., 2014), the appraisal of action-related concepts (controlled for outcomes on non-action processes) emerged as the *best* classifier between subjects in the anodal-M1 and sham-M1 groups –with an accuracy of 74%. The selective decrement observed thus seems systematic across subjects, and not merely the sum of proto-effects within the sample. Indeed, this analysis shows that outcomes from subsamples of subjects (training folds) achieve high classification rates in other subsets (testing folds), attesting to the inter-individual robustness of the results. Compatibly, action outcomes in narratives also constitute the most accurate variable for classifying patients with motor-network damage from healthy participants, even surpassing validated clinical tools (García et al., 2018). Therefore, the contribution of M1 to action appraisal in naturalistic texts seems inter-individually robust.

Furthermore, the anodal-M1 effect remained unchanged after co-varying for WM and PPVT-III scores, thus proving independent of the subjects' mnesic skills and general vocabulary knowledge. By the same token, differential and specific action-semantic deficits in movement disorders prove selectively uninfluenced by domain-general impairment (Ibáñez et al., 2013), even in text-level tasks (García et al., 2017, 2018). Likewise, the selective effects of bodily training on action understanding in naturalistic narratives are unaffected by WM skills (Trevisan et al., 2017). Similarly, here, the observed action-specific effect seems unmediated by extra-linguistic factors, which supports its potential generalizability beyond individual variability in relevant, coarser-grained domains.

Importantly, our results do not imply that motor networks are the *sole* substrate of action-related meanings, as recognized by rivaling frameworks which argue for primary (García et al., 2019, 2020; Pulvermüller, 2013, 2018) or non-primary (Caramazza et al., 2014; de Zubicaray et al., 2013; Hickok et al., 2011; Mahon & Caramazza, 2008; Papeo et al., 2013) roles of embodied mechanisms during language processing. In fact, processing of action semantics modulates activity in non-motor circuits, such as the anterior temporal lobe (García et al., 2019; Liljeström et al., 2008) and the left posterior middle temporal gyrus (Wurm & Caramazza, 2019), and it can be disrupted by transient perturbations of the latter region (Papeo et al., 2014). However, the claim that motor circuits are crucial for action appraisal is not undermined by evidence showing an important role of other regions. In fact, several semantic (Pulvermüller, 2018; Ralph et al., 2017) and embodied (Birba et al., 2017;

Pulvermüller, 2013, 2018) frameworks, including the HANDLE model (García & Ibáñez, 2016b), acknowledge that action-verb processing relies on complementary contributions of modality-specific and multimodal (mainly temporal and temporo-parietal) conceptual regions, with the latter supporting the formation of higher-level concepts through the integration of unimodal inputs from diverse brain regions –the timing of these effects has been extensively discussed elsewhere (García et al., 2020; Hickok, 2014; Papeo et al., 2014; Pulvermüller, 2018). In this sense, the selective M1 effect detected in our study should not be taken to reflect an *exclusive* role of such region in action-semantic processing.

5. Limitations and avenues for further research

Despite its contributions, our work features some limitations. First, the size of the groups was relatively small. Although other studies have yielded informative results with even smaller samples (Branscheidt et al., 2017; Liuzzi et al., 2010), future works should implement our approach with more participants. Second, the number of testing items was limited. However, previous versions of this paradigm have yielded robust condition-specific effects with ten (García et al., 2018) and even eight (Trevisan et al., 2017) trials per condition. Although our use of 20 items per condition doubles the *N* of previous studies, future adaptations of our protocol should expand this figure. Third, we did not test for polarity-specific effects. While exclusive use of offline anodal tDCS in our study is well motivated given its proven role in decreasing performance in action-language (Gijssels et al., 2018) and motor-related (Amadi et al., 2015; Apsvalka et al., 2018; Stagg et al., 2011) paradigms, future work including a cathodal tDCS condition could offer useful complementary data. Finally, due to the electrodes' size (25 cm²), our design had sub-optimal spatial resolution. Thus, stimulation effects may have reached regions beyond the target areas. Given that stimulation over M1 may have possibly extended to the premotor cortex, which is also systematically implicated in grounding action language (Hauk et al., 2004; Pulvermüller, 2013, 2018), further studies could aim to tease apart the role of different motor regions in the observed outcomes.

6. Conclusion

In conclusion, this study offers unprecedented evidence that offline, anodal modulation of M1 excitability triggers selective difficulties in the appraisal of action meanings evoked by naturalistic narratives. This pattern proves regionally specific, systematic at an individual level, and uninfluenced by the subjects' WM and vocabulary skills, attesting to its distinctiveness and potential generalizability. Therefore, motor circuits seem to play a non-trivial role in grounding modality-specific concepts across unfolding texts. By offering a direct tie among NIBS, the embodied cognition framework, and naturalistic approaches to neurolinguistics, our study lays fertile ground to understand the causal mechanisms underlying language processing from an ecological perspective.

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Fig. 1 –.

Experimental session. (A) Offline stimulation phase. First, the ‘motor hotspot’ (M1) was identified in each subject through single-pulse TMS as the optimal scalp position at which stimulation produced a noticeable twitch from the relaxed contralateral FDI muscle. Then, tDCS was applied at 2 mA for 20 min in the anodal-M1 and anodal-VLPFC groups, and for 30 sec in the sham-M1 group. (B) Behavioral testing phase. Participants were instructed to listen carefully to the recorded texts (two NTs and two ATs). Immediately after each text, the volunteer was presented with the corresponding questionnaire and asked to choose the correct answer as quickly as possible. The texts and their corresponding questionnaires were counterbalanced among participants. M1: primary motor cortex; VLPFC: ventrolateral prefrontal cortex TMS: transcranial magnetic stimulation; tDCS: transcranial direct current stimulation; AT: action text; NT: neutral text.

Fig. 2 –.

Results from the naturalistic narrative task. (A) Results from the sham-M1, anodal-M1, and anodal-VLPFC groups. For the anodal-M1 group, outcomes for verb-related information in the ATs (realized by action verbs and verb phrases) decreased significantly relative to circumstantial information in the AT and verb-related information (realized by non-action verbs and verb phrases). For the sham-M1 and anodal-VLPFC groups, outcomes for circumstantial and verb-related information was statistically similar in both text types. (B) Intra-category differences. Circumstance subtraction analyses showed no differences across groups. Verb subtraction analysis corroborated that anodal stimulation over M1 selectively decreased outcomes for process-related information for ATs compared to sham-M1 group. Values on the Y-axes indicate percentage scores. Asterisks (*) indicate significant differences, and double asterisks (**) indicate significant differences after covariation for working memory and vocabulary outcomes. (C) ROC curves for the subtraction between

verb-related information in the AT and the NT (green line), and circumstantial information in the AT and the NT (pink line) across groups (M1 *vs* sham; VLPFC *vs* sham; VLPFC *vs* M1). AT: action text; NT: neutral text.

Table 1 –

Linguistic features of the texts.

	Action text 1	Action text 2	Neutral text 1	Neutral text 2	<i>p</i> -values
Characters	941	908	976	934	.47 ^c
Words	207	203	204	199	.98 ^c
Nouns	48	48	44	43	.93 ^c
Adjectives	7	8	9	10	.90 ^c
Adverbs	6	8	8	8	.94 ^c
Verbs	32	32	32	32	1 ^c
Action verbs	24	28	1	2	X ² = 9.94, <i>p</i> < .001. Tukey's HSD tests showed that each NT differed from both ATs (<i>ps</i> < .001), with no differences between NTs or ATs (all <i>ps</i> > .58)
Non-action verbs	8	4	31	30	
Mean content word frequency	1.64 (.08)	1.67 (.08)	1.79 (.08)	1.79 (.08)	
Mean content word familiarity	6.17 (.08)	6.00 (.09)	6.28 (.08)	6.23 (.09)	.38 ^d
Mean content word syllabic length	2.50 (.08)	2.50 (.09)	2.44 (.09)	2.52 (.09)	.11 ^d
Mean content word Orthographic length	5.95 (.19)	5.70 (.19)	6.03 (.19)	5.93 (.19)	.88 ^d
Mean content word imageability	5.17 (.16)	5.27 (.17)	4.96 (.16)	4.89 (.17)	.63 ^d
Mean target verb frequency	1.08 (.16)	1.48 (.17)	1.10 (.18)	1.43 (.17)	.33 ^d
Mean target verb familiarity	5.61 (.36)	6.20 (.28)	6.23 (.34)	6.09 (.30)	.22 ^d
Mean target verb syllabic length	2.63 (.19)	2.4 (.18)	2.88 (.19)	2.66 (.17)	.58 ^d
Mean target verb orthographic length	6.00 (.44)	6.50 (.46)	7.44 (.49)	6.55 (.49)	.35 ^d
Mean target verb imageability	6.45 (.42)	6.70 (.44)	7.55 (.46)	6.55 (.46)	.19 ^d
Complex sentences (including subordinate clauses)	7	7	8	8	.31 ^d
Comprehensibility	4.5 (.20)	4.10 (.19)	4.38 (.19)	4.18 (.19)	.99 ^c
Coherence	4.0 (.22)	3.52 (.21)	4.00 (.21)	3.73 (.21)	.44 ^d
Grammatical Correctness	4.45 (.18)	4.14 (.17)	4.24 (.17)	4.36 (.17)	.32 ^d
					.28 ^d

	Action text 1	Action text 2	Neutral text 1	Neutral text 2	<i>p</i> -values
Reading difficulty ^a	79.38	79.93	77.9	75.09	.98
Readability ^b	Fairly Easy	Fairly easy	Fairly Easy	Fairly easy	-
Emotional valence (main effect of text)	33.38 (1.40)	33.54 (1.40)	33.33 (1.40)	33.23 (1.40)	.99 ^d
Arousal (main effect of text)	2.02 (.12)	2.40 (.12)	2.14 (.12)	2.44 (.12)	$F(240,3) = 2.82, p = .04$, Tukey's HSD test (DMS = .43 $df = 240$) showed no differences among the for texts (all $ps > .05$)
Number of voiced segments	184	202	177	228	.21 ^c
Number of silence segments	61	61	60	64	.23 ^c
Fundamental frequency (Hz)	115.05 (27.24)	111.6 (27.09)	112.6 (26.1)	115.83 (26.36)	.3871 ^d
Energy (dB)	10.29 (12.29)	11.61 (13.489)	9.5 (12.02)	10.03 (12.19)	.3893 ^d

^aMeasured through the Szigriszt-Pazos Index.

^bMeasured through the Inflezs scale.

^c*p*-values calculated with chi-squared test.

^d*p*-values calculated with independent measures ANOVA, considering text as a factor.