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HD-tDCS Over Motor Cortex Facilitates Figurative and Literal Action Sentence Processing

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Abstract

The extent to which action and perception systems of the brain are involved in semantic comprehension remains controversial. Whether figurative language, such as metaphors and idioms, is grounded in sensory-motor systems is especially contentious. Here, we used high-definition transcranial direct current stimulation (HD-tDCS) in healthy adults to examine the role of the left-hemisphere motor cortex during the comprehension of action sentences, relative to comprehension of sentences with visual verbs. Action sentences were divided into three types: literal, metaphoric, or idiomatic. This allowed us to ask whether processing of action verbs used in figurative contexts relies on motor cortex. The results revealed that action sentence comprehension response times were facilitated relative to the visual sentence control. Significant interaction relative to visual sentences was observed for literal, metaphoric, and idiomatic action sentences with HD-tDCS of the motor cortex. These results suggest that the left motor cortex is functionally involved in action sentence comprehension. Furthermore, this involvement exists when the action content of the sentences is figurative. The results provide evidence for functional links between conceptual and action systems of the brain.

Keywords

semantics; action; tDCS; embodiment; metaphor

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Authors contributions
KJ and NR equally contributed to this work. RD designed the study. SM and NR collected the data. MM, KJ, and SM analyzed the data. KJ, NR and RD wrote the paper. All authors read and confirmed the final version of the paper.

1. Introduction

Conceptual or semantic processing is widely distributed in the brain. Across concepts of many types, lateral and medial temporal cortex, as well as inferior parietal cortex are important for semantic processing (Binder & Desai, 2011; Binder, Desai, Graves, & Conant, 2009). One question that continues to be debated is the extent to which action and perception systems play a role in conceptual processing. Neuroimaging studies have found activation of action-perception systems for processing words or sentences that load on features related to action and perception (Desai, Binder, Conant, Mano, & Seidenberg, 2011; Desai, Binder, Conant, & Seidenberg, 2010; Fernandino, Humphries, Conant, Seidenberg, & Binder, 2016; Kiefer, et al., 2012; Martin, 2016). Clinical studies have further supported this view by showing that patients with impaired action-perception systems manifest more deficits in words with high motor content compared to low motor content (Desai, Herter, Riccardi, Rorden, & Fridriksson, 2015; Johari, et al., 2019; Riccardi, Yourganov, Rorden, Fridriksson, & Desai, 2020; Riccardi, Yourganov, Rorden, Fridriksson, & Desai, 2019). For example, in Parkinson's disease, it has been found that action verbs (e.g., *running*) are more impaired than non-action verbs (e.g., *thinking*), and this deficit is associated with the dysfunction of the dopaminergic system and its projections to the sensorimotor system (Fernandino, et al., 2013a). This notion is further supported by studies that showed better performance for action semantics during ON vs. OFF Levodopa in Parkinson's patients (Boulenger, et al., 2008).

Brain stimulation studies have also provided insight into functional role of action-perception systems in concept processing (Pulvermuller, Hauk, Nikulin, & Ilmoniemi, 2005). For example, transcranial magnetic stimulation (TMS) studies have found that stimulation of the primary motor cortex (M1) slows down behavioral performance for action-related words compared to abstract words (Vukovic, Feurra, Shpektor, Myachykov, & Shtyrov, 2017). Additionally, TMS disruption of M1 compromised learning of novel action verbs when motor information was critical for lexico-semantic processing (Vukovic & Shtyrov, 2019). This causal relationship between action semantics and sensorimotor systems has been further bolstered by TMS studies of sentence processing, with a recent study demonstrating that stimulation of M1 impaired the comprehension of sentences involving literal (e.g. *The spike was hammered into the ground*) or metaphoric action (e.g. *The army was hammered in the battle*) verbs (Reilly, Howerton, & Desai, 2019).

Consistent with TMS studies, transcranial direct current stimulation (tDCS) has also highlighted the role of action-perception systems in conceptual processing (Branscheidt, Hoppe, Freundlieb, Zwitserlood, & Liuzzi, 2017; Branscheidt, Hoppe, Zwitserlood, & Liuzzi, 2018). tDCS is a non-invasive method that provides causal associations between target regions of the brain and their functions. tDCS offers polarity-specific modulations without directly eliciting action potentials, representing a distinctive approach on relationship between brain and behavior (Filmer, Dux, & Mattingley, 2014). These studies have found that cathodal tDCS over motor and pre-motor cortex enhanced the learning of novel action words and accelerate response time for existing action words compared to abstract words in healthy subjects (Gijssels, Ivry, & Casasanto, 2018; Liuzzi, et al., 2010). Moreover, a recent study in post stroke aphasia found that anodal tDCS over left motor cortex improved action related word performance compared to object related words, supporting the view that action-related words are grounded in the motor system (Branscheidt, et al., 2018).

A recent innovation to the tDCS technique uses multiple electrodes in a configuration that determines the electric field orientation and current intensity on target regions (Ho, et al., 2016; Rawji, et al., 2018). As determined through modeling of the generated electric field, the stimulation provided by this High-Definition tDCS (HD-tDCS) technique is more focal than what can be achieved with traditional tDCS (Alam, Truong, Khadka, & Bikson, 2016). Moreover, it has been found that HD-tDCS stimulation can lead longer lasting effects after stimulation (more than 2 hours; Kuo et al. 2013) compared to traditional tDCS (Kuo, et al., 2013). This wider time window of post-stimulation effect offers greater opportunity to examine the variety of tasks in a single experimental session, which was more suitable for the purpose of current study. An additional advantage of tDCS is the blind nature of sham condition, in that subjects are unable to distinguish real or sham stimulation in most instances. This is usually not the case with TMS. One disadvantage of tDCS is its lower spatial resolution compared to TMS. Here, we used HD-tDCS, which provides significantly improved spatial resolution compared to traditional tDCS (DaSilva, et al., 2015; Dmochowski, Datta, Bikson, Su, & Parra, 2011; Garnett & den Ouden, 2015).

The goal of present study was to examine the functional effects of cathodal HD-tDCS over the hand area of the left-hemisphere M1 during the processing of action verbs used in sentence contexts. To our knowledge, no previous studies have examined the relationship between motor cortex and literal/figurative action verb processing in sentential contexts using HD-tDCS. We selected the hand region for stimulation because our verbs were mainly related to hand/arm actions (see Methods section). We asked whether processing sentences that used action verbs (e.g., *pour, twist*) would be modulated by polarization of the motor cortex. As a control for general linguistic processing and task effects not specific to action semantics, we used sentences with vision-related verbs (e.g., *see, view*). Differential modulation of action vs. vision sentences, relative to sham or control stimulation, would provide evidence of a functional role of motor cortex in processing action sentences. Several studies have used abstract sentences as controls. However, abstract concepts activate left inferior frontal regions (Wang, Conder, Blitzer, & Shinkareva, 2010), which are also associated with actions. We chose sentences with visual verbs as a control in order to minimize potential confounds related to either indirect action or executive processing associated with many abstract verbs.

We also asked a second question that relates to actions expressed in figurative or literal contexts, by dividing action sentences into three types: literal action (e.g., *The firefighter is pouring water around the building*), metaphoric (e.g., *The demand always pushed the prices up*), and idiomatic (e.g., *The automobile industry pressed the panic button*). The three types of action sentences can be thought of as representing increasing levels of abstraction. In a metaphor such as *grasp a theory*, an action verb is used on an abstract entity to convey an abstract concept (understanding a theory). An idiom such as *grasp at straws* is even more abstract, in that the entire idiom can be thought of as a single unit that is retrieved whole, without necessarily processing individual words at depth. Thus, second goal of the study was to examine whether modulatory effects of tDCS apply also to metaphoric and idiomatic action sentences, where no physical action is implied.

The question of involvement to action-related brain areas for figurative action sentences has been somewhat controversial due to inconsistent findings. Desai, Conant, Binder, Park, and Seidenberg (2013) found that a higher order action area in the anterior inferior parietal cortex was activated by literal and metaphoric action sentences, but not by action idioms that used the same verbs. This suggested that idioms are abstracted away from the action-perception system, such that an abstract meaning can be retrieved directly without grounding in the motor system. Fernandino, et al. (2013b) examined processing of the same sentence types in Parkinson's patients, and found that both literal and idiomatic action sentences were impaired in patients relative to abstract sentences. Boulenger, Hauk, and Pulvermuller (2009) reported activation in the motor cortex in a somatotopic manner for action idioms. During reading of idioms, rapid activation of motor cortex was reported by Boulenger, Shtyrov, and Pulvermuller (2012) in a MEG study. In a TMS study, Cacciari, et al. (2011) found motor-evoked potentials (MEPs) were modulated for both metaphoric and fictive motion sentences due to TMS, but not for idiomatic motion. Reilly, et al. (2019) found that both literal and metaphoric sentences were modulated by single-pulse TMS to hand motor cortex, whereas idiomatic sentences were not examined in this study. Other fMRI studies have also reported activation for action or perception regions for processing metaphors related to action, (Aziz-Zadeh, Wilson, Rizzolatti, & Iacoboni, 2006), texture (Lacey, Stilla, & Sathian, 2012), and body parts (Lacey, et al., 2017). Overall, evidence for grounding in the motor cortex is strong for (non-idiomatic) metaphors, considering both neuroimaging and brain stimulation studies. For idioms, it is less consistent.

Here, we first test the hypothesis that HD-tDCS on motor cortex specifically modulates action-related sentences. We examined the three action sentence types individually (literal, metaphoric, idiomatic) to investigate the role of the motor cortex in processing figurative (metaphoric or idiomatic) action sentences, which may shed light on the debate above. We hypothesized that each action sentence type, relative to the visual control, will be modulated by HD-tDCS of motor cortex. We also examined action sentences as a group to test for a main effect of action verbs and explored interactions among action sentence types to test the hypothesis that figurative action sentences may differ from literal action sentences.

2. Method

2.1. Subjects

Twenty-three right-handed subjects participated in the present study (10 females; mean age 24.2, SD 3, range 18–29; mean number of years of formal education 16.3, SD 2.4, range 12–19). Two subjects were excluded due to the high and unstable impedance of electrodes during stimulation (>100kΩ), leaving 21 subjects for analysis. They had normal vision and hearing, with no reported history of neurological and psychiatric disorders nor speech language impairments. The study was approved by the University of South Carolina Institutional Review Board. Informed consent was obtained from all individual participants included in the study. Subjects were either paid or received extra credits for their participation.

2.2. Materials

The stimuli consisted of 160 sensible sentences and 60 nonsense sentences (the full list of stimuli is provided in the Supplementary Materials). For each stimulation session, we used 80 sensible and 30 nonsense sentences. The task required subjects to respond, by using one of two different response keys, whether a sentence was meaningful or nonsense. The sensible sentences contained 120 action and 40 visual sentences. The action sentences were used in two previous studies (Desai, et al., 2013; Fernandino, et al., 2013b) and contained action verbs (e.g., *pinch, push, twist*). The action sentences were further divided into equal groups of literal action (e.g. *The firefighter is pouring water around the building*), non-idiomatic metaphoric action (e.g. *The demand always pushed the prices up*), and idiomatic action (e.g. *The automobile industry pressed the panic button*). The 40 sentences in each of the action-related sentences were formed by combining a single set of action verbs associated with hand/arm actions with different noun phrases. The stimuli were constructed in triples such that the same action verb was used in three contexts. The agents denoted by the noun phrases were selected so as to direct interpretation of the verb toward either a literal or a figurative meaning. The subject of the literal action sentences was a person (e.g., *The firefighter*) whereas for figurative sentences, it was an entity (e.g., *The automobile industry*) that is unlikely to perform physical actions. This decision was made to encourage a figurative interpretation even by the time the verb is encountered. The verbs in visual sentences were all were vision-related verbs (e.g., *see, view, perceive*). The idiomaticity of the idiomatic sentences as well as non-idiomatic status of the metaphoric sentences was verified by an online idiom dictionary compiled from the Cambridge International Dictionary of Idioms and the Cambridge Dictionary of American Idioms (http://idioms.thefreedictionary.com). The four conditions were matched in sentence length, (number of letters, number of phonemes, number of syllables and number words) as well as response time (RT) and accuracy (Acc), according to English Lexicon Project (ELP, Balota, et al. (2007); all p>.05). Nonsense sentences were grammatically correct and used the same verbs, but were difficult to make sense of (e.g. *The business is pinching the sunset*). All experimental parameters (e.g., timing of trials and randomizing) were administered with Eprime (Psychology Software Tools, Pittsburgh, PA). For each subject, half of the sentences from each condition (20 for each sensible sentence type, and 30 for nonsense sentences) were used during stimulation of the targeted area, while the other half was used during sham stimulation. These halves were counterbalanced across subjects.

2.3. Procedure

Subjects received cathodal and sham stimulation over left-hemisphere hand motor cortex for 20 minutes, applied with an M×N HD-tDCS Stimulator (Soterix Medical Inc., NY, USA). The configuration of the electrodes and their corresponding current intensities are displayed in Table 1. HD-Explore™ software (Soterix Medical Inc., NY, USA) was used for optimal electrode configurations, based on current simulation. Figure 1 shows the electrode locations and anatomical position of the target area over the left-hemisphere hand motor cortex (MNI: x=−57, y=3, z=14) and the modeled pattern of current flow intensity for cathodal and sham HD-tDCS, respectively.

To administer HD-tDCS, a standard 10–20 EEG cap (Easy-Cap GmbH, Germany) was placed on the subject's head, with the Cz position midway between inion and nasion, and between the two mastoids. The control stimulation was an 'active sham', where stimulation was administered for the entire 20 minutes but in a montage where the current was modeled to bypass the cortex (Davis, Gold, Pascual-Leone, & Bracewell, 2013; Garnett & den Ouden, 2015; J. D. Richardson, et al., 2014) and have minimal stimulation of the target motor cortex. Four electrodes were placed in proximal pairs so that the current was flowing in and out at adjacent electrodes. To better disguise sham by having equal numbers of electrodes on the participant's scalp across stimulation types, an additional electrode that did not administer any current was added so that five electrodes are positioned on the scalp in every condition. Particularly with high-definition multiple-electrode configurations, the sham method often used in traditional tDCS is to ramp up and then ramp down the current to induce the sensation of stimulation onset, but this may not be sufficient to fully neutralize differences in sensitivity between active and sham stimulation (J. Richardson, Datta, Dmochowski, Parra, & Fridriksson, 2015). Even though a low level of excitation/inhibition of neurons under the sham electrodes cannot be completely ruled out with an active sham used here, this was not expected to substantially affect responses to motor reaction time tasks (Ambrus, et al., 2012; Kessler, Turkeltaub, Benson, & Hamilton, 2012).

The experiment was conducted in a sound attenuated booth. Sentences were displayed on a screen in their entirety and presented in a pseudo-random order. Subjects were asked press one key on the keyboard if the sentence made sense, and another key if it did not. The order of keys was counterbalanced. Practice was given before the task. During the neurostimulation session, subjects performed a non-language distraction task (silently working on a jigsaw puzzle) and started doing the tasks immediately after the stimulation finished. The order of the stimulation sessions was counterbalanced between the subjects. Half of the subjects received cathodal stimulation in the first session following with sham stimulation in the second session. The rest of subjects received sham and cathodal stimulations in first and second sessions, respectively. Stimulation sessions were separated by at least 24 hours (range: 1 to 24 days). Subjects were not aware of the type of stimulation they were receiving in each session. Two other tasks dealing with lexical semantics were also included in the experimental session: lexical decision and semantic similarity judgment. The lexical decision task consisted of real verbs and nouns and pronounceable pseudowords presented to the participant one-at-a-time. The participant pressed one of two buttons to indicate whether the word was real or not. The semantic similarity judgment task consisted of verb or noun word triplets presented on the screen in a triangular array. The participant must indicate, via button press, which of the bottom two words was most similar in meaning to the top. For a complete description of the psycholinguistic properties of the words used in these tasks, see (Desai, et al., 2015; Riccardi, et al., 2020; Riccardi, et al., 2019). The order of the three tasks was counterbalanced across participants. Within each participant, the order of the three tasks was kept the same for both real and sham stimulation sessions. The lexical decision and semantic similarity judgment tasks measure lexical semantic processing below the sentence level and are therefore beyond the scope of the current manuscript, which focuses specifically on verb processing in sentential contexts. Each experimental session lasted around 1 hour, with 15–20 minutes being devoted to the sentence task depending on participant response speed.

2.4. Data analysis

The response time for each condition was obtained by the time difference between stimuli presentations and subjects' response on the keyboard. For each subject, trials ± 3 SD away from the mean were considered outliers and were excluded from statistical analysis. The outlier percentages were similar across sentence and stimulation type (below 3%). All statistical analyses were performed in R (R-Core-Team, 2014).

2.4. Statistical analysis

To examine the effect of stimulation on reaction time, linear mixed effects (LME) model was used with stimulation type (cathodal vs. sham) and sentence type (literal, idiomatic, metaphoric vs. visual) as a fixed factor, and subjects as random factor[1]. We also adopted random intercepts and random slopes (Barr, Levy, Scheepers, & Tily, 2013). Follow up analyses were performed to compare three action sentences with visual sentences separately.

Critically, the hypotheses concern the interaction between stimulation (cathodal, sham) and sentence type (action, vision). The absolute values and main effects are not relevant to the hypotheses. Because the task involved a physical action (pressing a button), stimulation of motor cortex was expected to affect all conditions, which interacts with any effects due to sentence semantics. Changes in RTs of individual conditions due to stimulation cannot be meaningfully interpreted in terms of semantics, due to effects on the button-press action, and other general effects of tDCS. Only a stimulation x sentence type interaction can indicate whether there is a differential effect of stimulation depending on the sentence type, which can be attributed to semantics. The interactions are equivalent to computing a "net RT" (cathodalRT-shamRT) for each condition, and comparing conditions with a t-test, with the difference that directional testing is possible for t-tests (Fernandino, et al., 2013b; Howell, 2012). Finally, an LME model was used to compare response time for idiomatic and metaphoric sentences with literal sentences.

Cathodal stimulation is often thought of as 'inhibitory' stimulation, and 1 mA stimulation often shows inhibitory effects (Furubayashi, et al., 2008; Medeiros, et al., 2012). However, experimental findings have shown that 2 mA stimulation of the motor cortex for 20 min results in excitability enhancement rather than inhibition (Batsikadze, Moliadze, Paulus, Kuo, & Nitsche, 2013). Studies of language processing are also consistent with this finding, where cathodal stimulation at 2 mA results in facilitation or faster response times (Gijssels, et al., 2018). Facilitation with cathodal stimulation is seen even outside of motor cortex. Faster picture naming responses were observed with cathodal simulation over inferior frontal as well as inferior parietal areas (Garnett, Malyutina, Datta, & den Ouden, 2015). Hence, we used one-tailed statistics in the direction of facilitation relative to the control condition. The nonsense sentences contained a mix of verbs with majority being action related, were only used as 'catch trials,' and were excluded from the main statistical analysis.

[1]. RT ~ Sentence type + Stimulation + Sentence type *Stimulation + (1 + Stimulation|Subject)

3. Results

3.1. Stimulation effect action sentence compared to visual sentences

The mean and standard errors are shown in Table 2. LEM analysis revealed a 4 (sentences type)×2(stimulation) significant interaction ($F_{(3, 2956.43)}$ =2.87, p =0.015).

Follow up planned comparisons with sentence type (visual vs. each action sentence type) and stimulation (sham vs. cathodal) yielded to significant interaction (equivalent to t-tests using net RTs mentioned above) for visual vs. literal ($F_{(1, 1538.8)}$ = 6.9582, p <0.0001) , visual vs. idiomatic ($F_{(1, 1416.93)}$ = 5.80, p=0.008), and an interaction for visual vs. metaphoric ($F_{(1, 1510.3)}$ = 2.733, p=0.045). (Figure 2). The interaction arose from an increase in RT for the control condition, relative to a flat response or a small decrease in RT for the action sentences. Thus, compared to the baseline of visual control sentences, action sentences demonstrated relative facilitation due to simulation.

Collapsing across the action sentence types, a significant interaction was seen between action and visual sentences ($F_{(1, 2959.72)}$ = 7.56, p < 0.0001) . Results from nonsense sentences were not of interest and are inherently difficult to interpret. We note that because majority of the nonsense as well as sensible sentences were action related, it is not surprising that nonsense sentences also showed an effect that patterned with that of the action sentences.

3.2 Effect of stimulation on literal vs. metaphoric and idiomatic sentences

LME analysis did not reveal significant interactions between stimulation and action sentence type: literal vs. idiomatic ($F_{(1, 1410.461)}$ = 0.0009, p=0.46) and literal vs. metaphoric ($F_{(1, 1510.3)}$ = 0.94, p=0.15) sentences. This suggests similar effects of stimulation for all three action sentence types.

4. Discussion

The present study investigated the effect of HD-tDCS centered over the left-hemisphere motor cortex on sensibility judgment reaction times for action and visual sentences. We found an interaction such that HD-tDCS to motor cortex significantly facilitated performance on literal, idiomatic, and metaphoric action sentences relative to the visual control condition. No interaction between the three action sentence types was seen. These results show that modulation of the left motor cortex has an effect on sentence comprehension, and that the effect of this modulation differs depending on the action-related content of the sentences.

4.1. Action sentences compared to visual

Several investigations of action language processing have demonstrated that primary and higher-order motor cortices are activated by, and functionally involved in, the comprehension of action-related language. This evidence comes from a variety of methods, including neuroimaging (Aziz-Zadeh, et al., 2006; Desai, et al., 2013), neurostimulation (Pulvermuller, et al., 2005; Reilly, et al., 2019; Vukovic, et al., 2017), and patient studies (Desai, et al., 2015; Kemmerer, Rudrauf, Manzel, & Tranel, 2012; Riccardi, et al., 2020;

Riccardi, et al., 2019). The current finding, that 2 mA cathodal M1 stimulation resulted in relative facilitation of action language processing compared to the visual condition, aligns well with facilitation effects in action language processing in both tDCS and TMS studies (Gijssels, et al., 2018; Pulvermuller, et al., 2005; Willems, Labruna, D'Esposito, Ivry, & Casasanto, 2011). Batsikadze et al. (2013) showed increased excitability for 2 mA cathodal as well as anodal tDCS over motor cortex, with increased MEP amplitudes. Increased excitability can lead to effects of stimulus/response congruence. Responding via button press for visual sentences can be thought of as an 'incongruent' condition, leading to relative increase in RTs compared to sham. Action sentences describing actions performed with the right hand and response via the same hand is congruent, leading to relative facilitation. In other words, motor tDCS has a general effect on task performance due to the button press, which interacts with any semantic effects, due to which changes in individual conditions cannot be meaningfully interpreted as semantic. Only condition x stimulation interactions, which account for the general effects of tDCS on task performance, can show effects of sentence semantics.

4.2 Action sentences comparisons

Both metaphoric and idiomatic sentences showed an effect of stimulation. For the metaphor condition, the results support the previously discussed evidence implicating the action-perception system in action metaphor comprehension (Cacciari, et al., 2011; Desai, et al., 2013; Reilly, et al., 2019). Regarding action idioms, previous findings have been less consistent, with some studies finding evidence of action-perception system involvement (Boulenger, et al., 2012; Fernandino, et al., 2013b) while other studies suggest that idiomatic meanings are abstracted away from action-perception systems (Cacciari, et al., 2011; Desai, et al., 2013). The present results suggest that the left M1 and surrounding motor cortex does, within the spatial resolution of HD-tDCS, have a functional link to the comprehension of action-related figurative language, even in the case of idioms. These results were found even though literal interpretations of action verbs in figurative sentences was discouraged by choosing noun phrases unlikely to produce or evoke physical actions (i.e., *The company*) as agents. Hence, results are unlikely due to noun-related priming of literal action simulation. Relative contribution of the hand primary motor cortex versus nearby regions in the precentral and postcentral gyri, typically associated with action schemas, cannot be distinguished given the spatial resolution of HD-tDCS.

Non-compositional models of idiom processing suggest that idioms are stored and retrieved as chunks of constructions (e.g., Gibbs, 1994a; Swinney & Cutler, 1979). This view proposes that idioms are processed as single lexical items associated with the abstract meaning. Compositional models propose that idioms are analyzed compositionally at some level, and single words can have influence on its interpretation (e.g., Cacciari & Tabossi, 1988; Hamblin & Gibbs, 1999). Hybrid models that take elements of both proposals also exist (Titone & Connine, 1999). The current results support compositional and hybrid models, by showing that action idioms are grounded in the motor system at some level and are not necessarily processed as abstract lexical items.

While no interaction was observed between different action conditions, the numerical magnitude of effects for metaphors was somewhat weaker compared to literal and idiomatic sentences. We speculate that this may reflect some contribution from the right hemisphere in metaphor comprehension. Neuroimaging and behavioral evidence suggests that, compared to literal language or highly conventionalized metaphors, the right hemisphere is preferentially involved processing novel metaphors, especially in sentential contexts (Lai, van Dam, Conant, Binder, & Desai, 2015; Mashal & Faust, 2008, 2009; Yang, 2014). Even though metaphors used in this study were not designed to be novel or creative, a tentative suggestion is that increased involvement of the right hemisphere when processing metaphoric sentences may explain the numerically weaker effect of left M1 stimulation for action metaphors.

An ongoing controversy in figurative language comprehension has been between direct access models (Gibbs, 1994b; Glucksberg, 2008) and indirect access models (Janus & Bever, 1985; Searle, 1979). These models assume that there are two distinct meanings – a literal meaning and an abstract/figurative meaning – associated with metaphors. Direct access models state that the figurative meaning can be accessed directly without intervening access to the literal meaning. Indirect access models claim that the literal meaning is accessed first, followed by the abstract meaning. We dispute this underlying assumption of two distinct meanings. The figurative and supposedly abstract meaning can in fact be based in the literal sense, blurring the binary distinction between the literal and the metaphoric. As proposed by Reilly, et al. (2019), it is possible that action verbs, even when used figuratively, possess a motor component that is: (1) partially grounded in action-perception systems of the brain and (2) accessed somewhat automatically. Such a view is also consistent with the Underspecification Model of figurative language (Frisson & Pickering, 2001). This model argues that, during comprehension, a single and underspecified meaning of a word is activated, which is later refined. We suggest that in the case of action verbs, this underspecified meaning includes the word's motor components, among other attributes. The underspecified meaning is then 'honed' through context, leading to eventual comprehension of the metaphor.

Future studies can examine the role of the right-hemisphere motor cortex during figurative and literal action sentence comprehension. Evidence suggests that right-hemisphere action-perception areas can support action-related semantic processing via connectivity to left-hemisphere areas following disruption of the left-hemisphere (Riccardi, et al., 2020; Riccardi, et al., 2019), raising the possibility that right-hemisphere areas could compensate for the effects of left-hemisphere stimulation alone. The question of laterality is also especially relevant for figurative language comprehension, as there is an ongoing debate regarding the specialization of the right-hemisphere for figurative language (Bohrn, Altmann, & Jacobs, 2012; Kasparian, 2013; Rapp, Mutschler, & Erb, 2012). tDCS provides a unique opportunity for future investigations to stimulate a single hemisphere, or both hemispheres simultaneously, allowing for an in-depth investigation of laterality effects in language processing.

4.4 Conclusion

The present study investigated the effect of HD-tDCS over the left-hemisphere motor cortex on sensibility judgement reaction times for action and visual sentences. Action sentences as a whole were affected differentially by stimulation, suggesting a functional role of motor cortex in their processing. Metaphoric and idiomatic action sentences were also affected selectively by this stimulation relative to control sentences. This suggests that the functional link between action language and motor cortex is maintained for figurative use.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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- HD-tDCS applied to left motor cortex while subjects read action sentences
- Action sentences showed relative facilitation with stimulation
- This facilitation was also seen for metaphoric and idiomatic action
- Functional role of motor cortex in action language processing

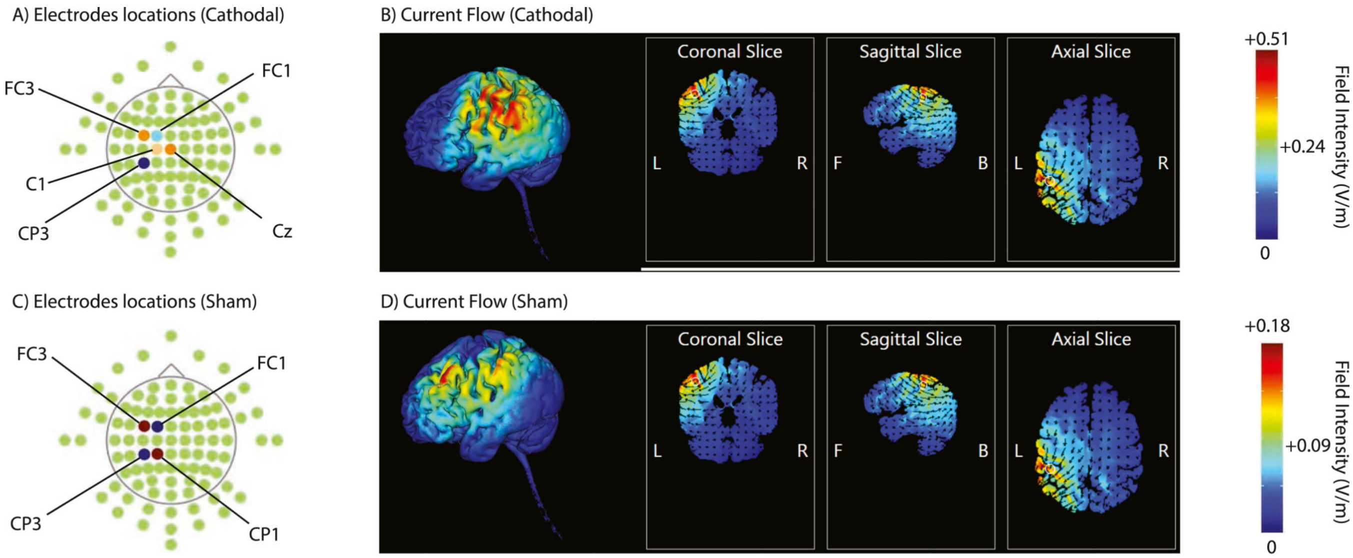

Figure 1.
illustrates the location of electrodes for **A)** cathodal & **C)** sham stimulations. Panel **B** & **D** show the current follow for cathodal and sham stimulations, respectively. Note, the colorcoding scale of field intensity are different for cathodal (panel B) and sham (panel D) stimulations.

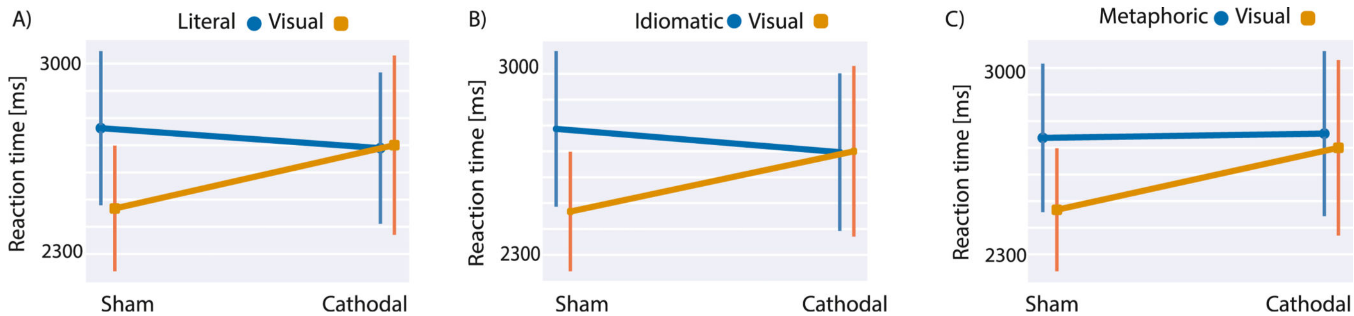

Figure 2.

Comparison of the effect of stimulation on reaction times for A) literal action, **B)** idiomatic, and C) metaphoric sentences relative to visual sentences. Error bars display standard errors of means.

Table 1.

Electrodes configuration, current density and field intensity for Cathodal and sham stimulations.

Cathodal			Sham		
Location	**Current**	**Field Intensity in Left Hand**	**Location**	**Current**	**Field Intensity in Left Hand**
CP3	−1.85 mA	0.51 V/m	FC3	+1 mA	0.05 V/m
Cz	+0.88 mA		FC1	−1 mA	
C1	+0.14 mA		CP1	+1mA	
FC3	+0.84mA		CP3	−1 mA	
FC1	−0.01mA				

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Table 2.

Shows means and standard errors of RTs for different sentence types, separately for cathodal and sham conditions.

	Sentence types					
Group	**All action**	**Idiomatic**	**Literal**	**Metaphoric**	**Visual**	**Nonsense**
Cathodal	2714 ± 297	2697 ± 304	2689 ± 278	2754 ± 310	2700 ± 330	2790 ± 319
Sham	2761 ± 287	2787 ± 301	2763 ± 284	2734 ± 279	2467 ± 231	2935 ± 350