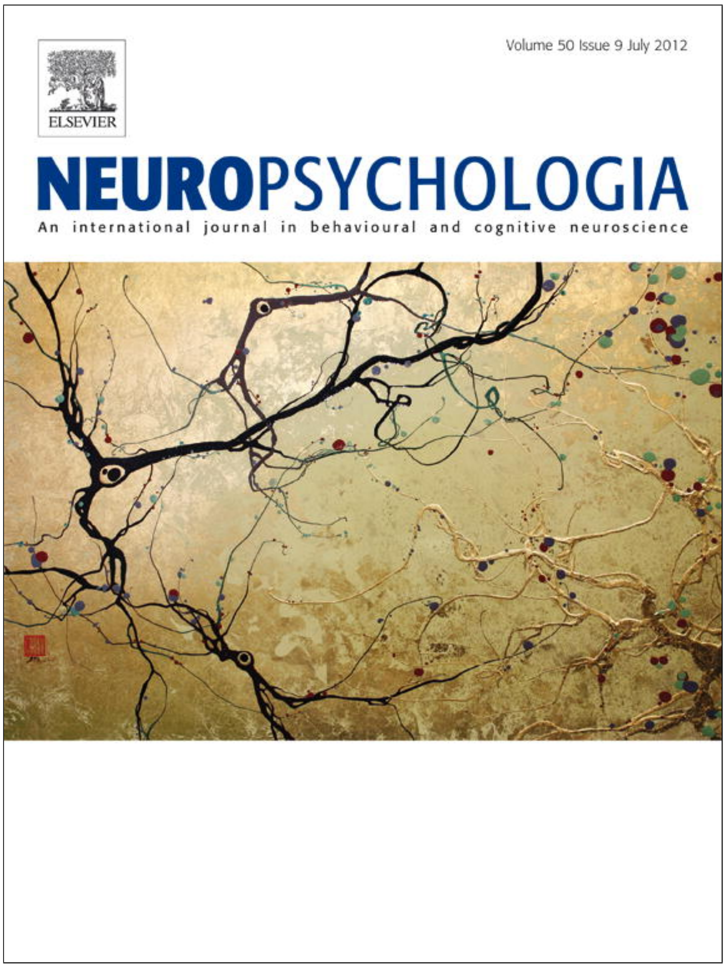
Volume 50 Issue 9 July 2012
ELSEVIER
NEUROPSYCHOLOGIA
An international journal in behavioural and cognitive neuroscience

Neuropsychologia 50 (2012) 2271–2280

Contents lists available at SciVerse ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Prefrontal control during a semantic decision task that involves idiom comprehension: A transcranial direct current stimulation study

Tal Sela [a], Richard B. Ivry [b], Michal Lavidor [a,c,*]

[a] Department of Psychology, Bar Ilan University, Ramat Gan 52900, Israel
[b] Department of Psychology, University of California, Berkeley, CA 94720-1650, USA
[c] Department of Psychology, University of Hull, Cottingham Road, Hull HU6 7RX, UK

ARTICLE INFO

Article history:
Received 13 November 2011
Received in revised form
12 March 2012
Accepted 29 May 2012
Available online 9 June 2012

Keywords:
Semantic processing
Cognitive control
tDCS
DLPFC
Trait motivation
Idioms

ABSTRACT

Language processing and comprehension can be understood in terms of both linguistic and non-linguistic processes. To make a decision regarding the meaning of complex linguistic inputs such as idiomatic expressions, one has to perform multiple complex cognitive operations such as prediction, selection and inhibition. In the current study, we used transcranial direct current stimulation (tDCS) to test the hypotheses that (I) a prefrontal cognitive control network is involved in directing decisions required for the comprehension of idioms, and (II) that this prefrontal control may be biased by motivational mechanisms. Participants were randomly allocated to one of two stimulation groups (LH anodal/RH cathodal or RH anodal/LH Cathodal). Over a one-week interval, participants were tested twice, completing a semantic decision task after either receiving active or sham stimulation. The semantic decision task required participants to judge the relatedness of an idiom and a target word, with the idiom being predictable or not. The target word was either figuratively related, literally related, or unrelated to the idiom. Each participant also completed a trait motivation questionnaire and a control task. After DC stimulation, a general deceleration in reaction times to targets was found. In addition, the results indicate that the neural enhancement of a left lateralized prefrontal network improved performance when participants had to make decisions to figurative targets of highly predictable idioms, whereas the neural enhancement of the opposite network improved participants' performance to literal targets of unpredictable idioms. These effects were more pronounced in individuals rated as being most sensitive to reward likelihood. The results are discussed in terms of cognitive control over semantic processing.

1. Introduction

Cognitive control is a construct that incorporates aspects of high order processes that enable the formation, maintenance, and updating of goal representations (Miller & Cohen, 2001). Such representations provide a top-down biasing signal to enhance or inhibit information processing (Banich et al., 2000; Miyashita, 2004; Savine & Braver, 2010). One important question concerns how cognitive control operations influence semantic processing. Specifically, how might goals bias information retrieval from semantic memory, and contribute to selection processes when there are competing semantic meanings. The primary aim of the current study was to examine how the experimental manipulation of activity in dorsolateral prefrontal cortex (DLPFC; Brodmann's Area 9/46), a region associated with cognitive control functions (Koechlin, Ody, & Kouneiher, 2003; MacDonald, Cohen, Stenger, & Carter, 2000), may affect performance on a semantic decision task that involves the comprehension of idiomatic expressions.

In order to modulate DLPFC neural excitability, we used a non-invasive stimulation technique, transcranial direct current stimulation (tDCS). tDCS is a painless cortical stimulation technique that has been shown to induce short-term changes in cortical excitability (Nitsche & Paulus, 2000). The physiological effects of tDCS have been reported to last for about 1 h after several minutes of continuous stimulation in humans (Nitsche & Paulus, 2000; Nitsche et al., 2003) and have been linked with neurophysiological mechanisms of long-term potentiation and depression (Nitsche et al., 2003). While the physiological effects of tDCS are not as focal as that offered by transcranial magnetic stimulation (TMS), it does have three, distinct advantages. First, the effects of tDCS can be bi-directional, with anodal tDCS causing neural depolarization, thus enhancing cortical excitability, and cathodal

* Corresponding author at: The Gonda Multidisciplinary Brain Research Center, Bar Ilan University, Ramat Gan 52900, Israel. Tel.: +972 3 5318171; fax: +972 3 5352184.
E-mail address: michal.lavidor@gmail.com (M. Lavidor).

0028-3932/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.neuropsychologia.2012.05.031

tDCS causing neural hyperpolarization and decreased cortical excitability (Nitsche & Paulus, 2000, 2001). Second, the method affords a highly reliable sham condition (Gandiga, Hummel, & Cohen, 2006) in which the stimulation is turned on and off over a relatively short period time, with the participants having being unable to distinguish this condition from real stimulation. Third, if the two electrodes are both placed over cortical areas, tDCS can be used to simultaneously increase excitability in one region and decrease excitability in another region (Fecteau et al., 2007; Hecht, Walsh, & Lavidor, 2010).

Behaviorally, tDCS studies have examined performance across a number of task domains including working memory (Fregni et al., 2005), language learning (Flöel, Rösser, Michka, Knecht, & Breitenstein, 2008) and visual recognition memory (Boggio et al., 2009). With respect to DLPFC stimulation, anodal tDCS has been shown to improve performance on language-related tasks such as verbal fluency (Iyer et al., 2005) and picture naming (Fertonani, Rosini, Cotelli, Rossini, & Miniussi, 2010), as well as in tests of probabilistic classification (Kincses, Antal, Nitsche, Bartfai, & Paulus, 2004) and probabilistic guessing (Hecht et al., 2010). The latter is particularly interesting given the importance of prediction and prior work linking the DLPFC to prediction across various cognitive domains (see Bubic, von Cramon, & Schubotz, 2010 for a review).

Predictive mechanisms play an essential role in human language processing and comprehension (Vespignani, Canal, Molinaro, Fonda, & Cacciari, 2009). Similar to perceptual tasks (Bar, 2007, 2009), language based communication relies upon the successful interplay between previously processed information, the information currently being processed, and predictions arising from the combination of these two information sources (Roehm, Bornkessel-Schlesewsky, Rosler, & Schlesewsky, 2007). Prediction can constrain the search through semantic memory and facilitate the processing of anticipated information (Kutas & Federmeier, 2000). For example, DeLong, Urbach, and Kutas (2005) demonstrated that readers can rapidly and incrementally integrate incoming words into an evolving mental representation based on probabilistic predictions of the forthcoming words.

While prediction processes could operate solely on the basis of learned associations, cognitive control operations can also help constrain predictions. For example, in visual search tasks, maintaining the target in working memory (e.g., a red and white striped hat) facilitates detection. Similarly, in language, an appreciation of linguistic and non-linguistic goals and intentions may shape predictions generated during online comprehension (see also Kan and Thompson-Schill, 2004). Idiom comprehension in this regard provides an interesting venue for the investigation of cognitive control over semantic processing, since they entail interesting variation in terms of predictability and semantic relatedness. Idioms comprehension may requires the coordinated operation of complex cognitive processes such as prediction, selection and inhibition (Canal, Vespignani, Molinaro, & Cacciari, 2010; Papagno, 2010). For example, understanding an idiom such as "He cried over spilled milk" requires the listener to generate predictions related to different potential meanings, and to predict the most relevant idiomatic meaning. In this process of interpretation, different semantic representations may be activated, with some concepts highly relevant to the expression and context (e.g., loss, complain) while others irrelevant, or potentially distracting (e.g., cow, liquid).

Idioms, by definition, have both an idiomatic and literal meaning. The activation of these is influenced by the predictability of the idiom. Cacciari and Tabossi (1988) reported that the idiomatic meaning of highly predictable expressions was accessed sooner than that of less predictable expressions. In contrast, the literal meaning of less predictable phrases was activated sooner than that of highly predictable phrases. According to their configurational hypothesis (Cacciari and Tabossi, 1988; see also Canal et al., 2010), the individual components of an idiom are analyzed as normal lexical items until a key part triggers the recognition of the idiomatic nature of the phrase, leading to the activation of the figurative meaning. With the recognition of the idiomatic key, the literal meaning no longer continues to accumulate activation, although it is not completely suppressed. By this view, cognitive control processes could influence comprehension by becoming engaged when the phrase is recognized as an idiom.

In terms of the neural correlates of semantic processing, Jung-Beeman's fine-coarse semantic coding theory (Jung-Beeman, 2005), proposes that the left hemisphere (LH) represents fine (close) semantic relationships, while the right hemisphere (RH) supports broader semantic fields, fields that are capable of representing both close and distant semantic relationships. In support of this hypothesis, the RH appears to be more adept in retrieving and maintaining semantic activations requiring atypical interpretations (Beeman & Bowden, 2000; Bowden & Jung-Beeman, 2003). Neuroimaging and EEG data also agree with the notion of the relative importance of the RH for coarse processing (Jung-Beeman et al., 2004).

A recent ERP study by Proverbio, Cortti, Zani, and Adorni (2009) explored semantic decision-making in the context of idiom comprehension. Subjects had to decide whether idiomatic or literal sentences were semantically related or unrelated to a following target word. The ERP data indicated that both hemispheres were initially engaged during processing, with the source generators associated with left fusiform gyrus, and bilateral medial frontal cortex (250 ms post-stimulus). Subsequently, the activation pattern became more bilateral and even exhibited some right hemisphere asymmetries over middle temporal gyrus and medial frontal gyrus. These activations are consistent with the hypothesized role of the right hemisphere in the evaluation/comprehension of idiomatic meaning (Jung-Beeman, 2005). Proverbio et al. (2009) also documented the involvement of the medial prefrontal cortex during comprehension of idioms, a finding that may support the view that idiom processing is PFC dependent (Lauro, Tettamanti, Cappa, & Papagno, 2008; Papagno, 2010), consistent with the hypothesis that the comprehension of idioms entails processes associated with cognitive control. Functional imaging studies of idiom comprehension have also reported bilateral activations of temporal, frontal and prefrontal sites (e.g., Lauro et al., 2008; Zempleni, Haverkort, Renken, & Stowe, 2007). Interestingly, in comparison to the comprehension of literal sentences, idiom comprehension is associated with increased activation of bilateral, fronto-temporal regions including PFC (Lauro et al., 2008). The authors interpreted the PFC activation as a reflection of control operations required to select the most suitable meaning of the idioms.

We set out to extend this line of research, examining the hypothesis that, as part of a cognitive control network, the DLPFC helps evaluate the predictive value of idioms to help constrain processing, and to direct semantic related decision making processes. To test this hypothesis, two groups of participants were given LH anodal/RH cathodal or RH cathodal/LH anodal tDCS, and sham tDCS, before completing a semantic decision task and a control task. We predicted that tilting the balance between left and right DLPFC with tDCS would have differential effects on performance in a semantic decision task that involves the comprehension of idiomatic expressions. The semantic decision task required participants to explicitly judge the relatedness of an idiom and a target word, with the idiom being predictable or not, and the word being figuratively related, literally related, or unrelated. We predicted that enhancement of a left lateralized prefrontal network (LH anodal/RH cathodal) would promote the activation of a top-down control over semantic processing in the LH. As such, this stimulation should improve performance when predictable idioms are followed by their most expected semantic meanings (e.g., figurative targets), reflecting the activation of close semantic relationships. Enhancement of a right lateralized prefrontal network (RH anodal/LH cathodal) should improve the activation of a top-down control over semantic processing in the RH. This will result in improved performance when unpredictable idioms are followed by their most expected semantic meanings (e.g., literal targets), reflecting the activation of both close and distant semantic relationships.

A second aim of the current investigation was to explore whether individual differences in trait motivation modulate tDCS effectiveness. It has been argued that motivational variables might influence the prioritization of behavioral goals (Pessoa, 2008, 2009). Given recent evidence implicating left DLPFC served as a key neural locus for the integration of cognitive and motivational information (Savine & Braver, 2010), we predicted that enhancement of this area would influence these interactions. trait motivation level was assessed with the BIS/BAS scales (Carver & White, 1994) that are designed to measure two independent systems linked to motivation (Gray, 1987; Gray & McNaughton, 2000; Pickering & Gray, 1999). The Behavioral Approach System (BAS) is hypothesized to regulate responses to rewarding stimuli; the Behavioral Inhibition System (BIS) is hypothesized to regulate inhibitory processes to aversive stimuli. The BAS system has been linked to the LH (Spielberg et al., 2011; Sutton & Davidson, 1997). Moreover, neuroimaging and EEG evidence point to a LH frontal locus, especially with respect to reward seeking (Berkman & Lieberman, 2009; Coan & Allen, 2003; Harmon-Jones & Allen, 1997; Sutton & Davidson, 1997). Furthermore, activity in the left DLPFC has been found to associate with "reward bias," an enhanced tendency to respond to reward-related cues (Pizzagalli, Sherwood, Henriques, & Davidson, 2005). We hypothesized that individual motivational tendencies related to trait approach motivation might moderate tDCS effects on executive control components of the given task, and predicted that individual variation on the BAS scales would influence performance changes induced by tDCS in task performance.

2. Materials and methods

2.1. Participants

Participants in the experiment were 24 healthy subjects (mean age $= 25.23 \pm 2.65$; range 22–31 years, 10 male, 14 female). They were all right-handed as assessed by the Edinburgh Handedness Inventory (handedness score ≥ 90; Oldfield, 1971), native Hebrew speakers and free from any history of psychiatric or neurological disorders. The participants gave informed consent under a protocol approved by the local ethics committee and in accord with The Code of Ethics of the World Medical Association (Declaration of Helsinki). Two participants were excluded from the analysis (one from the LH anodal/RH cathodal group and one from the RH anodal/LH cathodal group) due to technical problems.

2.2. Stimuli and pretests

2.2.1. Idioms

An idiom database in Hebrew was created (based on Hebrew idiom dictionaries; Fruchtman, Ben-Nathan, & Shani, 2001; Rosenthal, 2009), with each idiom composed of a word string, 3–4 elements long. 192 items were selected and were evaluated for different psycholinguistic properties such as predictability, literality, transparency and figurativeness (see also Supplemental material A).

Cacciari and Tabossi (1988) view predictability as a process that promotes access to the idiomatic configuration. They defined prediction as the proportion of responses in which the phrase was completed idiomatically when its final word is omitted. Given the aims of the current study, we used only idioms in which this predictability "property" was restricted to the last word. To evaluate predictability, a list of idioms was presented to 15 native speakers of Hebrew ($M = 29.33$, $SD = 6.16$). These participants were instructed to complete a sentence with the first word that comes to mind (e.g., He kicked the ______).

Another group of Hebrew speakers ($N = 18$, $M = 26$, SD $= 4.10$) were presented with the same list of idioms, and were asked to make judgments of literality. Literality refers to an idiom's potential to have a literal interpretation (Titone & Connine, 1994). For example, 'bite the bullet' has a well-formed literal meaning; other idioms such as 'break her word', only have a meaningful idiomatic interpretation. Participants were asked to rate if there is a possible literal interpretation to the idiom, using a 7-point scale in which 1 indicated that the idiom did not have a possible literal interpretation and 7 indicated that it definitely has a clear and well-formed literal interpretation.

A third group of native speakers of Hebrew ($N = 14$, $M = 26.14$, $SD = 5.24$) were recruited to assess the figurative meaning of the idioms. These participants were instructed to write down the meaning of the idiom. Five judges, all native speakers of Hebrew, were instructed to compare the participants' answers with the dictionary meaning of the idiom (Fruchtman et al., 2001; Rosenthal, 2009) deciding with a dichotomous scale if the participant gave a wrong (0) or correct (1) answer. Based on these ratings a new scale—'Actual Meaning', was derived and taken to indicate the knowledge the subjects had of the meaning of the idioms.

Another group of native speakers of Hebrew ($N = 17$, $M = 24.05$, SD $= 3.21$) were presented with the same list of idioms and asked to make judgments of transparency. Idioms can involve figuration and be metaphorical ("take the bull by the horns"), even if the comprehenders may not always know the precise meaning (Nunberg, Sag, & Wasow, 1994). Other idioms do not involve figuration. In transparent expressions, speakers can wholly recover the rationale for the figuration involved. This is not the case for opaque idioms (Oliveri, Romero, & Papagno, 2004). Participants were asked to rate how easily the meaning of the idiom could be deduced from the idiom on a score ranging from 1 (not at all—"opaque") to 7 (entirely—"transparent"). Pearson's correlations coefficients between the four psycholinguistic factors were calculated (see Table 1; for further elaborations on the primacy of predictability see Supplemental material B).

Based on the median predictability score (Med $= 0.4$; Range: 0–1), the idioms list was divided into two groups—"Unpredictable" and "Predictable" idioms. The mean predictability scores were 0.13 ($SD = 0.13$) and 0.73 ($SD = 0.19$) for the unpredictable and predictable idioms, respectively. The predictable and unpredictable idioms also differed in the 'Actual Meaning' scores, with the participants having a better sense of the meaning of the predictable idioms ($M = 0.63$, $SD = 0.31$) compared to the unpredictable idioms [$M = 0.39$, $SD = 0.31$; Independent t-test: $t(190) = 5.1$, $p < 0.001$]. A similar result was evident with respect to transparency rating, with the participants rating predictable idioms as more transparent ($M = 4.99$, $SD = 1.1$) compared to the unpredictable idioms [$M = 3.95$, $SD = 1.27$; Independent t-test: $t(190) = 5.97$, $p < 0.001$]. The two groups did not differ in literality ratings [Unpredictable idioms: $M = 4.26$, $SD = 1.34$; Predictable idioms: $M = 4.51$, $SD = 1.51$; $t(190) = 1.2$, n.s].

2.2.2. Target words

The set of target words included three types of stimuli. 25% were unrelated words (e.g., 'Bite the bullet'—"Fashion"); 25% were literally-related words (e.g., 'Bite the bullet'—"Flavor"); 50% were figuratively-related target words (e.g., 'Bite the bullet'—"Accept"). Sixteen native speakers of Hebrew ($M = 25.07$, $SD = 3.54$) were asked to judge how well the idioms were related to the target words on a five-point scale ranging from one (highly unrelated) to five (highly related). We choose only highly related (mean relatedness score > 4.5) or highly unrelated (mean relatedness score < 1.5) idiom–target pairs. All target words were nouns and matched for length [mean (length) $\pm$ SD for: figurative target words—4.68 ± 0.90; literal target words—4.50 ± 0.90; unrelated target words—4.75 ± 0.91]. We also compared their frequency, entering each word in a Google search (www.google.co.il) and recording the number of hits, based on prior work showing that the number of hits produced by a search engine is a good approximation of frequency (Blair, Urland, & Ma, 2002). This method indicated that the target words were well-matched in terms of frequency [mean Log 10 (frequency) $\pm$ SD: figurative target words—5.98 ± 1.01; literal target words—5.95 ± 1.15; unrelated target words—5.78 ± 1.13].

Table 1
Pearson's correlations among different idiom psycholinguistic factors.

	(1)	(2)	(3)	(4)
(1) Predictability	–			
(2) Literality	0.113	–		
(3) Transparency	0.41**	0.16*	–	
(4) Actual meaning	0.42**	0.09	0.64**	–

Note: $N = 192$.

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

2.3. General procedure

Each participant completed two identical experimental sessions separated by 1 week. In one session, active tDCS was applied; in the other, sham tDCS was used. Two tasks (see below) were administered immediately following the stimulation. Order of tasks, as well as stimulus list of each task, was counterbalanced across participants. Additionally, at the beginning of the first session, participants completed the BIS/BAS scales.

2.3.1. Semantic decision task

Participants performed a semantic decision task (Fig. 1A), which lasted approximately 10 min. There were six conditions, formed by the factorial combination of the predictability of the idiom and the target type (Fig. 1B). The 192 idioms were divided into two lists of 96 items each, with the lists equated in terms of predictability. One list was used for each session. The order of the lists was randomized between participants and across conditions. Order of the idioms and targets were randomized within each list.

The participants were comfortably seated in a quiet dark room, 60 cm from the screen. The screen sampling rate was 60 Hz. The stimulus display was controlled by E-prime 1.1 software (Psychology Software Tools, Inc., PA, US). The participants were presented with short instructions on screen, followed by eight practice trials (that were not used afterwards) in which they received feedback following each response. Following a short debrief, the stimulation experiment began. After 15 min of stimulation, the subjects performed the experimental task, which included 96 trials without feedback. Each trial began with the presentation of a fixation cross for 500 ms. The cross was replaced by an idiom which remained on the screen for 2000 ms. Participants were instructed to read the idioms silently. The fixation cross reappeared for 750 ms followed by the target word for 180 ms. Participants indicated whether the idiomatic expression and the target word were related, pressing the right or left mouse keys. They were instructed to respond rapidly while maintaining a high level of accuracy.

2.3.2. Control task

To exclude the possibility that tDCS effect could be ascribed to a general enhancement of cognitive function, we included a control task, a spoonerism task, which assesses phonological awareness (Romani, Ward, & Olson, 1999). This task does not contain any explicit semantic component nor is it sensitive to the predictive value of the stimuli. In this task, which lasted approximately 5 min, participants were asked to swap the initial phonemes of two words (e.g., "sad cat" gives "cad sat"). The experimenter presented 20 Hebrew word pairs orally. Participants had to first repeat the phrase and then produce the spoonerism. Accuracy rates were recorded for each participant in both the sham and tDCS sessions. We used 20 Hebrew word pairs for each list and counterbalanced between the two lists, participants and conditions. All of the words were two syllables long.

2.4. tDCS

A double-blind, sham controlled, randomized method was used with respect to the stimulation conditions (see Fig. 2 for an overview of the study design). Participants were randomly assigned to one of two active stimulation groups (LH anodal/RH Cathodal or RH anodal/LH Cathodal). Within each group, the participants were tested two times separated by a 1-week interval, with the order of active and sham stimulation counterbalanced. For the active stimulation condition, a direct current of 1.5 mA intensity was induced by two $5 \times 7\ \text{cm}^2$ saline-soaked synthetic sponge electrodes and delivered by a battery-driven, constant-current stimulator (Magstim LtD, Wales). The current had a ramp-up time of 30 s, was held at 1.5 mA for 15 min, and then ramped down over 30 s. For sham stimulation, the current was ramped up over 30 s, and then immediately ramped down over 30 s. We used the international EEG 10/20 system to determine the DLPFC stimulation sites (e.g., Fecteau et al., 2007; Hecht et al., 2010). To stimulate left DLPFC, the anode electrode was placed over F3 and the cathode electrode over F4 (LH anodal/RH cathodal). The polarity was reversed to stimulate right DLPFC (RH anodal/LH cathodal).

2.5. Assessment of motivation

At the start of the first session, participants completed the BIS/BAS scales (Carver and White, 1994). All items were judged on a four-point scale ranging from 1 ('I strongly agree') to 4 ('I strongly disagree'). The BIS/BAS scales assess one behavioral

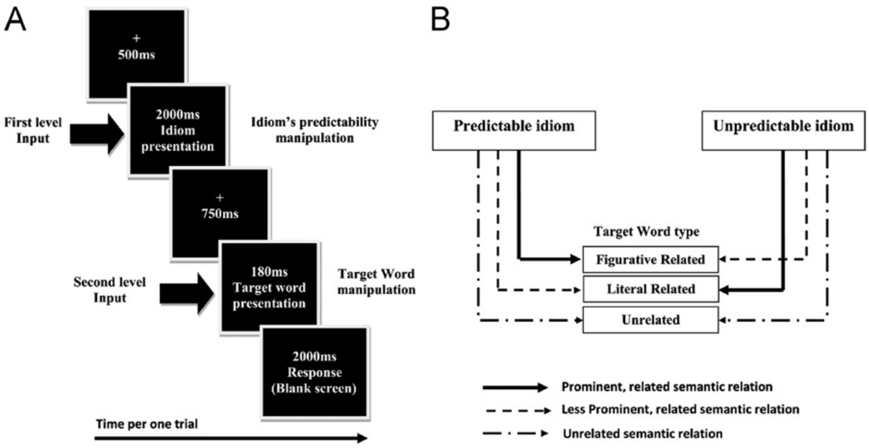

Fig. 1. (A) Semantic decision task: The trial began with the presentation of a fixation cross for 500 ms. The cross was replaced by an idiom which remained on the screen for 2000 ms. Participants were instructed to read the idioms silently. The fixation cross reappeared for 750 ms followed by the target word for 180 ms. Participants were instructed to indicate whether the idiomatic expression and the target word were related, pressing the right or left mouse keys. They were instructed to respond rapidly while maintaining a high level of accuracy. The next trial began after a 2000 ms interval. (B) Six experimental conditions: two experimental manipulations (2×3) have been used—idiom's predictability with two levels (predictable and unpredictable) and target word type with three levels (figurative related, literal related and unrelated). The conditions were a priori defined as being prominent, related semantic relations (continuous line), less prominent, related semantic relations (dash line) or unrelated semantic relations (dash–dot line).

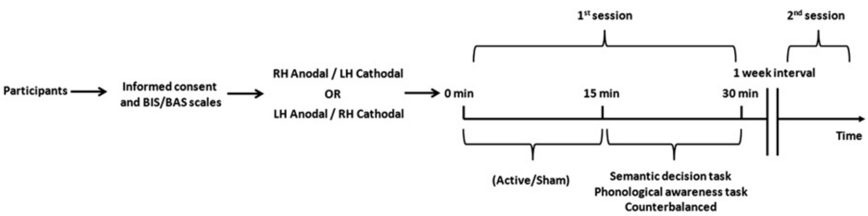

Fig. 2. Overview of the study design. After providing informed consent, participants completed the BIS/BAS scales (Carver and White, 1994). They were then randomly assigned to one of two stimulation conditions designed to enhance left or right DLPFC. Each participant was tested in two sessions, separated by a 1-week interval. Session order (Active/Sham) was randomized. Sham or DC stimulation lasted a total of 15 min, with a direct current of 1.5 mA intensity in the active stimulation. Immediately after the stimulation, participants performed the semantic decision and phonological awareness tasks, with the order counterbalanced across participants and conditions.

inhibition measure (BIS; e.g., "I worry about making mistakes") and three personality measures related to reward sensitivity: (1) The positive anticipation of rewarding events (BAS Reward Responsiveness—BAS-RR; e.g., "When I see an opportunity for something I like I get excited right away"). (2) Items tapping strong pursuit rewards (BAS Drive—BAS-D; e.g., "I go out of my way to get things I want"). (3) The tendency to seek out new rewarding situations (BAS Fun Seeking—BAS-F; e.g., "I'm always willing to try something new if I think it will be fun").

3. Results

The data from the semantic decision task were analyzed with a mixed AVOVA model that included two between-subject factors and two within-subject factors. The between factors were Stimulation Group (LH anodal/RH cathodal/RH anodal/LH cathodal) and Motivation Bias (BAS-RR+/BAS-RR−). For the latter, the participants were assigned to either the BAS-RR+ or BAS-RR− groups based on a median split of the data (BAS-RR+: $M=6.91$; SD=1.04; BAS-RR−: $M=10.45$, SD=0.93), with higher values indicating participants who were less sensitive to reward. The within factors were Idiom Predictability (Unpredictable/Predictable) and Word Type (Figurative/Literal/Unrelated). Separate ANOVAs were run using dependent variables of reaction time and accuracy. An accurate response was defined as a response in which participant successfully determined whether the target word was related to the idiom or not. Based on accuracy scores (see Table 2), we created an "Accuracy Change" variable. The percentage of change in accuracy was calculated for each participant in every stimulation condition by subtracting the sham accuracy score from the active accuracy score and dividing this number by the subject' sham accuracy score. Positive values correspond to an improvement in performance, whereas negative values correspond to a decline in performance. Similar calculations were used with respect to reaction time ("Reaction time Change"), with positive scores here corresponding to facilitation in performance and negative scores corresponding to a decline in performance. Both Accuracy Change and Reaction time Change scores were tested for normal distribution (using kurtosis and skewness values), as well as with Levene test of homogeneity of variance, and found to be normal distributed.

Accuracy change analysis (see also Supplemental material B): The accuracy change analysis revealed a crossover interaction of Stimulation Group × Predictability [$F_{(1,18)}=9.60$, $p<0.01$; $\eta_p^2=0.35$; see Fig. 3A]. For predictable idioms, participants' performance significantly improved with LH anodal/RH cathodal stimulation compared to RH anodal/LH cathodal stimulation [Independent *t*-test: $t_{(20)}=2.71$, $p<0.05$, $R^2=0.27$]. For unpredictable idioms, the reverse was observed: here, performance was better after RH anodal/LH stimulation compared to LH anodal/RH cathodal stimulation [Independent *t*-test: $t_{(20)}=2.42$, $p<0.05$, $R^2=0.23$].

The accuracy change analysis also revealed a significant 3-way interaction of Stimulation Group × Predictability × Word Type [$F_{(2,36)}=4.35$, $p<0.05$; $\eta_p^2=0.20$; see Fig. 3*B*], as well as a 4-way interaction of all of the factors [$F_{(2,36)}=9.60$, $p<0.000$; η_p^2 0.35]. The 3-way interaction reflects the fact that the Stimulation Group × Predictability interaction was limited to the conditions in which the target word was related to the idiom. For predictable idioms, performance was more accurate for figurative related target words after LH anodal/RH cathodal stimulation compared to RH anodal/LH cathodal stimulation [Independent *t*-test: $t_{(20)}=2.80$, $p<0.05$, $R^2=0.28$]. A similar pattern was observed when the predictable idioms were followed by literal related target words, but this effect was only marginally significant [Independent *t*-test: $t_{(20)}=1.6$, $p=0.075$]. For unpredictable idioms, performance was more accurate for literal related target words after RH anodal/LH cathodal stimulation compared to LH anodal/RH cathodal stimulation [Independent *t*-test: $t_{(20)}=2.43$, $p<0.05$, $R^2=0.23$]. All of the other comparisons related to the 3-way interaction were not significant ($t<1$).

In order to uncover the source of the complex 4-way interaction, we preformed a MANOVA with Stimulation Group and Motivation Bias as the independent variables, and the accuracy change measure as the dependent variable (a 2 × 2 design with six dependent variables). Stimulation Group was significant [Wilks' Lambda=0.41, $F_{(6,13)}=3.13$, $p<0.05$; $\eta_p^2=0.59$], with the same pattern as reported above. The analysis also revealed a 2-way interaction of Stimulation Group × Motivation Bias [Wilks' Lambda=0.36, $F_{(6,13)}=3.8$, $p<0.05$; $\eta_p^2=0.63$]. The univariate tests revealed that tDCS effects were limited to the BAS-RR+

Table 2
Mean percentage scores and standard deviations of accuracy scores for stimulation groups by motivation bias, DC condition, word type and idiom's predictability

Motivation bias	DC condition	Word type	Idiom's predictably	Stimulation group	
				LH anodal/RH cathodal	RH anodal/LH cathodal
BAS-RR+	Sham tDCS	Figurative word	Unpredictable idiom	75 ± 1.5	74 ± 1.5
			Predictable idiom	79 ± 0.6	85 ± 0.4
		Literal word	Unpredictable idiom	90 ± 0.7	76 ± 1.3
			Predictable idiom	73 ± 1.1	91 ± 1
		Unrelated word	Unpredictable idiom	83 ± 1.7	96 ± 0.4
			Predictable idiom	95 ± 0.8	94 ± 0.7
	Active tDCS	Figurative word	Unpredictable idiom	80 ± 1.3	77 ± 1.3
			predictable idiom	88 ± 0.3	80 ± 0.6
		Literal word	Unpredictable idiom	77 ± 0.8	94 ± 0.4
			Predictable idiom	89 ± 0.4	82 ± 1.1
		Unrelated word	Unpredictable idiom	88 ± 1	92 ± 0.8
			Predictable Idiom	87 ± 1.8	89 ± 1.1
	Sham tDCS	Figurative word	Unpredictable Idiom	80 ± 0.3	73 ± 0.6
BAS-RR−			Predictable idiom	83 ± 0.6	86 ± 0.5
		Literal word	Unpredictable idiom	87 ± 1.4	86 ± 1
			Predictable idiom	84 ± 1	93 ± 0.7
		Unrelated word	Unpredictable idiom	91 ± 0.9	78 ± 1.7
			predictable idiom	100 ± 0	98 ± 0.4
	Active tDCS	Figurative word	Unpredictable idiom	76 ± 1.2	75 ± 1.2
			Predictable idiom	83 ± 0.5	86 ± 1
		Literal word	Unpredictable idiom	87 ± 1.4	91 ± 0.8
			Predictable idiom	82 ± 0.9	92 ± 1.4
		Unrelated word	Unpredictable idiom	88 ± 0.9	86 ± 1.1
			predictable idiom	98 ± 0.4	93 ± 0.8

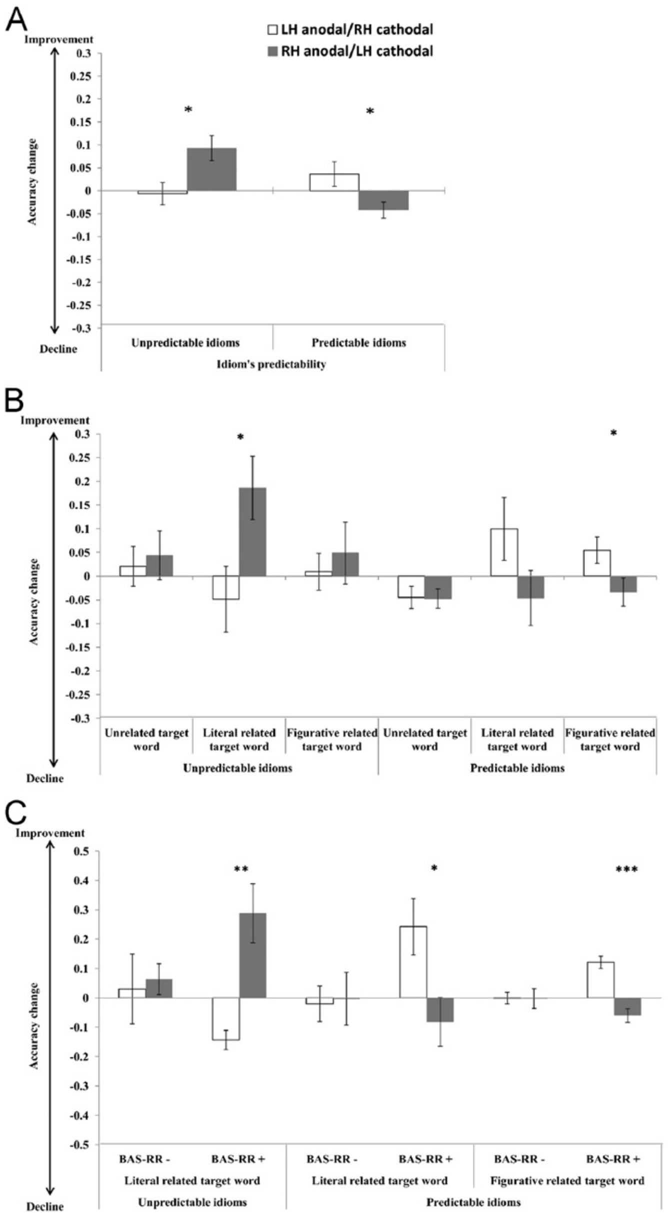

Fig. 3. Accuracy change scores (mean ± SE). (A) 2-way interaction showing the effect on accuracy was dependent on the stimulation configuration and predictability of the idioms. (B) 3-way interaction revealed that the tDCS effects were limited to specific idiom–target pairings. (C) tDCS effects were limited to individuals who rated themselves as highly sensitive to reward (BAS-RR+ group). (*$p<0.05$; **$p<0.01$; ***$p<0.001$).

group. For individuals rated as being more sensitive to reward responsiveness (see Fig. 3C), performance was more accurate after LH anodal/RH cathodal stimulation compared to RH anodal/LH cathodal stimulation in the predictable idiom–figurative related target word condition [Independent t-test: $t_{(9)}=5.64$, $p<0.000$, $R^2=0.78$], and in the predictable idiom–literal related target word condition [$t_{(9)}=2.57$, $p<0.05$, $R^2=0.42$]. In addition, performance for the BAS-RR+ participants was more accurate after RH anodal/LH cathodal stimulation in the unpredictable idiom–literal related target word condition [$t_{(6.05)}=4.09$, $p<0.001$, $R^2=0.58$]. The comparable t-values were <1 for the BAS-RR− group.

The BAS-RR moderation effect cannot be attributed to baseline differences in motivation between the two tDCS stimulation conditions. A chi-square test of independence conducted to examine the relation between BAS-RR ratings and tDCS conditions was not significant: χ^2 (1, $N=22$)=0.18, $p=0.67$. Furthermore, BAS-RR mean scores of the two groups did not significantly differ [LH anodal/RH cathodal $M=8.72$, $SD=2.24$; RH anodal/LH cathodal $M=8.64$, $SD=1.96$; Independent t-test: $t(20)=0.1$, $p=0.92$]. The two stimulation groups did not differ significantly in any other BIS/BAS parameter (see Table 3).

We further explored the relationship between BAS-RR scores and accuracy change scores. For this aim, we calculated BAS-RR standardized scores and accuracy change scores for the predictable idioms–figurative target word condition only. Negative standardized BAS-RR scores represents the participants tendency to rate themselves as sensitive to reward on this scale, whereas positive scores represents participants tendency to rate themselves as less sensitive to reward. Negative standardized accuracy change scores represents decline in performance compared to sham, whereas positive scores represents an improvement in performance compared to sham.

Correlations coefficients (see Fig. 4) between standardized scores of BAS-RR and accuracy change showed that, after LH Anodal/RH Cathodal stimulation, the more participants rated themselves as BAS-RR oriented (i.e., sensitive to reward), the greater their improvement in performance [$p<0.000$; $r_p(11)=-0.88$; $R^2=0.77$]. In contrast, after RH anodal/LH cathodal stimulation, the more participants rated themselves as BAS-RR oriented (i.e., sensitive to reward), the greater their decline in performance [$p<0.05$; $r_p(11)=0.65$; $R^2=0.42$]. To conclude, the relationship between the BAS-RR standardized measure and accuracy change scores following LH and RH enhancement (LH anodal/RH cathodal and RH anodal/LH cathodal, respectively) differed significantly, with the effect pronounced for individuals showing negative BAS reward responsiveness scores (BAS-RR+).

Reaction time change analysis: tDCS did not produce any significant effects on the RT change scores (all $F<1$). However, there was a trend for slower RT's after active stimulation compare

Table 3
Mean, standard deviations and median BIS/BAS Scores for the two stimulation groups.

BIS/BAS scales and subscales	Stimulation group		Independent t-test	Total	Total median
	LH anodal/RH cathodal	RH anodal/LH cathodal			
BIS	14.82 ± 3.43	14.00 ± 3.61	n.s	14.41 ± 3.46	14.5
BAS	25.91 ± 4.44	25.09 ± 4.28	n.s	25.5 ± 4.27	25
BAS drive	9.00 ± 1.95	7.91 ± 2.43	n.s	8.45 ± 2.22	9
BAS fun seeking	8.18 ± 1.83	8.55 ± 2.16	n.s	8.36 ± 1.97	8
BAS reward responsiveness	8.73 ± 2.24	8.64 ± 1.96	n.s	8.68 ± 2.06	8.5
BIS/BAS	−0.02 ± 1.15	0.02 ± 1.31	n.s	0.00 ± 1.38	−0.08

Note: BIS/BAS is not an original measure used by Carver and White (1994), but a later calculation to express behavioral prefrontal asymmetry index as described elsewhere (Sutton & Davidson, 1997).

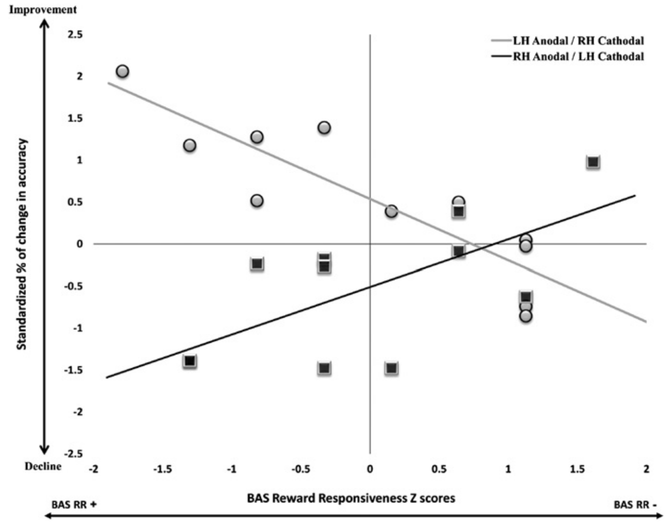

Fig. 4. Relationship between the standardized scores of BAS reward responsiveness and accuracy change differed following left and right DLPFC tDCS enhancement, with this effect pronounced for individuals showing negative BAS reward responsiveness scores (BAS-RR+).

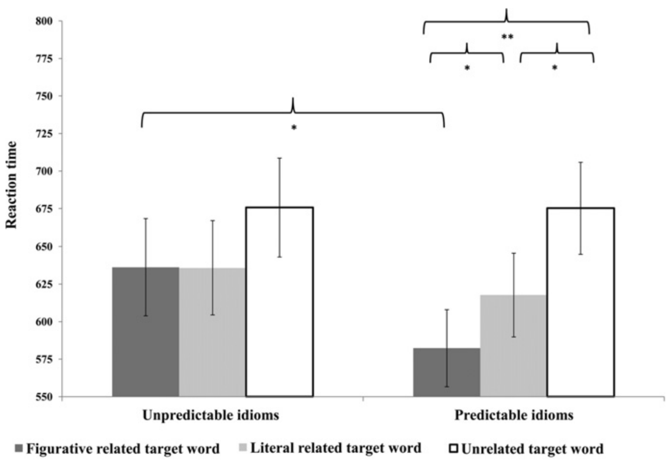

Fig. 5. Reaction time (mean ± SE) for a 2-way interaction between idioms predictability and idiom–target pairings (*$p < 0.05$; *$p < 0.01$).

to sham stimulation, regardless of stimulation site. A one-sample Student's *t*-test was performed to test the hypothesis that the change in RTs was different from zero. The mean change in RT ($M = -10\%$, SD = 18%) was significantly different from the hypothesized value of 0, [$t(21) = -2.42$, $p = 0.025$; 99% CI (-20.5% to 1.6%)]. Thus, compared to the sham condition, RTs were significantly slower after active tDCS.

We also examined the RT data to assess the effects of Idiom Predictability (Unpredictable/Predictable) and Word Type (Figurative/Literal/Unrelated), collapsed the data over Stimulation Group and Motivation Bias. The analysis revealed a main effect for Predictability [$F_{(1,21)} = 6.05$, $p < 0.05$; $\eta_p^2 = 0.22$], with faster RTs after predictable idioms ($M = 625.08$ ms, SE = 26.26) compared to unpredictable idioms ($M = 649.2$ ms, SE = 29.45). We also found a main effect for Word Type [$F_{(1.358,28.519)} = 8.08$, $p < 0.01$; $\eta_p^2 = 0.28$; Greenhouse-Geisser correction]. Post-hoc tests (Bonferroni correction) reveled that RTs to figurative target words ($M = 609.17$ ms, SE = 28.01) were faster compare to unrelated ($M = 675.57$ ms, SE = 30.9, $p = 0.004$). This effect was only marginally reliable for the literal target words compared to the unrelated target words ($M = 626.69$ ms, SE = 28.56, $p = 0.095$). Finally, we observed an interaction of Predictability × Word Type [$F_{(2,42)} = 3.65$, $p < 0.05$; η_p^2 0.15; see Fig. 5]. The results show that in the case of high predictable idioms, the RT advantage for figurative compared to both literal and unrelated was reliable. There was also a significant difference between the latter two conditions. However, no difference was found in the case of figurative targets when these targets followed unpredictable idioms. Furthermore, the results show that participants responded faster to figurative targets presented after predictable idioms compared to unpredictable idioms.

Performance on the spoonerism task was not affected by tDCS or motivational biases (all $F < 1$) nor did tDCS stimulation influence performance when the target words were unrelated to the idioms.

4. Discussion

In the current study, we investigated how tilting the balance between left and right DLPFC with tDCS influenced performance in a semantic decision task that involved the comprehension of idiomatic expressions. The results revealed an interaction involving the tDCS configuration and the relationship between the idioms and the target words. Moreover, the magnitude of the effect induced by tDCS was modulated by individual differences in trait motivation. We also found that reaction time was slower after DC stimulation, regardless of tDCS configuration. We hypothesize that the results highlight the manner in which cognitive control processes associated with the prefrontal cortex regulate semantic processing during idioms comprehension.

The neural enhancement of a left lateralized network boosted accuracy in classifying the relationship between the idiom and target word when the idiom was predictable. In contrast, enhancement of a right lateralized network boosts accuracy when the idiom was not predictable. This pattern is consistent with the hypothesis that predictable items primarily entail the recruitment of a fine semantic field whereas unpredictable items entail the recruitment of a distant semantic field (Jung-Beeman, 2005).

The crossover interaction was limited to specific idiom–word pairings. According to the configurational hypothesis (Cacciari and Tabossi, 1988), the anticipated and most accessible meaning of a predictable idiom is the figurative one, a representation that would be strongest in a fine semantic field. Predictability can constrain search through semantic memory, facilitating the processing of anticipated information (Kutas & Federmeier, 2000). In the current study, this constrained search was reflected in a decision regarding the figurative interpretation of a predictable idiom, and was improved after the neural enhancement of a left lateralized prefrontal network.

The neural enhancement of a left lateralized network (LH anodal/RH cathodal) also improved accuracy in classifying the relationship between the idiom and literal target word when the idiom was predictable. Several psycholinguistic studies have shown that people have difficulty suppressing the literal meaning of an idiom (e.g., Cacciari & Glucksberg, 1991; Titone & Connine, 1999). According to the configurational hypothesis (Cacciari & Tabossi, 1988), the processing of the literal meaning of an idiom is not terminated after the idiomatic meaning has been retrieved. It is possible that the neural enhancement of a left lateralized prefrontal network further maintained the accessibility to the literal meaning of a predictable idiom, helping the participants make a judgment that depended on this meaning.

Enhancement of a right lateralized prefrontal network (RH anodal/LH cathodal) mainly boosted accuracy when the idiom was unpredictable. Unlike predictable idioms, the most accessible, and thus predicted meaning of unpredictable idioms is the literal one (Cacciari & Tabossi, 1988). Our findings suggest that a right lateralized prefrontal network is crucial for the regulation of semantic relations that emerge after the presentation of unpredictable idioms. This suggestion seems reasonable given the RH bias for maintaining and retrieving close and distant semantic relationships (Beeman & Bowden, 2000; Bowden & Jung-Beeman, 2003; Jung-Beeman, 2005).

One interesting finding of the current study regards the increase in reaction time after active tDCS, regardless of tDCS configuration. It is possible that neural modulation of the PFC produced a general engagement of control processes, a consequence of which was that the participants took more time to ensure that they made the right decision. Rizzo, Sandrini, and Papagno (2007) observed an opposite effect after rTMS over PFC: RTs, after either left or right rTMS were faster when participants were asked to choose the appropriate meaning for both figurative and literal sentences, and there was a corresponding increase in errors when the sentences involved idioms. If we consider only predictable idioms followed by their figurative meaning (the most canonical form of idiom in the present design), our findings mirror this speed-accuracy trade-off. After the neural enhancement of a left lateralized prefrontal network participants were improved in accuracy, but were slower.

Overall, the results are consistent with the hypothesis that left and right lateralized prefrontal networks make a causal contribution to idiom comprehension. We propose that this contribution includes the generation of predictions that emerge as the idiomatic phrases are being processed online. Previous tDCS studies also showed the importance of DLPFC engagement in probabilistic predictions and learning (Hecht et al., 2010; Kincses et al., 2004). Moreover, the laterality pattern observed here would suggest that the PFC helps coordinate processing within task-relevant networks. Previous studies have shown that anodal tDCS over left DLPFC improved verbal fluency (Iyer et al., 2005) and picture naming (Fertonani et al., 2010). These tasks may all reflect a benefit of enhancing fine semantic fields, representations that are likely to be especially relevant in predictable contexts. These hypotheses are similar to the conclusions reached by Lauro et al. (2008) who used connectivity analysis to demonstrate how the anterior medial frontal gyrus has a prominent role in regulating the cross talk between perisylvian language areas during idiom comprehension (see also Fogliata et al., 2007; Rizzo et al., 2007). In the current study, such control operations over semantic relations were amplified by the different tDCS stimulation montages.

In the current study, tDCS effects were restricted to performance in the semantic decision task, and did not affect performance in the control task (i.e., the spoonerism task). While performance in the spoonerism task is associated emphasizes phonological processing, it would also seem to place demands on cognitive control operations (e.g., working memory). However, it is noteworthy that the spoonerism task does not involve an explicit semantic component. It may be that our control task was not sufficiently sensitive to detect changes induced by tDCS. Alternatively, it may be that the effect of tDCS on PFC function is most pronounced when the task requires the control over networks spanning large cortical areas (as in semantic retrieval). We also examined the influence of tDCS on motivational factors that might be moderators of idiom comprehension. We observed that variation on a trait motivation propensity (BAS reward responsiveness; BAS-RR) moderated the effects of tDCS (see Figs. 3C and 4). This finding has important implications regarding the impact of trait motivation on cognitive control, and in this context, on top-down regulation of language comprehension. The effects of tDCS were limited to the individuals in the BAS-RR+ group, that is, individuals rated as being more sensitive to reward responsiveness.

Motivational variables can enable prioritization of behavioral goals, thus influencing cognitive control (Jimura, Locke, & Braver, 2010; Pessoa, 2008, 2009; Savine & Braver, 2010; Spielberg et al., 2011; van Steenbergen, Band, & Hommel, 2009). Reward sensitivity, an affective component of personality, points to a particular endophenotype in which lateral PFC cognitive control mechanisms are selectively modulated (Jimura et al., 2010). Pizzagalli et al. (2005) claimed that the DLPFC is involved in maintaining goal representations and in anticipating future rewards or loss relative to goal related behavior. We suggest that tDCS have been selectively effective in influencing the performance of the BAS-RR+ group because these individuals are more sensitive to the predictive value of information.

Several limitations must be considered when interpreting the results of this study. First, the task makes it difficult to assess the effects of tDCS on idiom comprehension per se. We used an explicit semantic task without the literal fillers that are usually employed when comparing literal and figurative language comprehension (e.g., Proverbio et al., 2009). As such, we cannot say if tDCS had a selective effect on idiom processing.

Second, we have focused on the predictive property of the idioms. It is possible that other psycholinguistic characteristic of idioms (e.g., transparency, familiarity) are more important, and predictability may be confounded with them (see Supplemental material A). We opted to employ idioms because their variation in predictability and degree of semantic relatedness seemed desirable given our goal to study the effects of perturbing cognitive control mechanisms on language comprehension.

Third, it remains unclear how DLPFC contributes to prediction. We claim that the DLPFC displays a dual role during the semantic processing. During the early stages of processing, the DLPFC is sensitive to probabilistic information. Later on, as these predictions emerge, the DLPFC can help evaluate and select between different candidates, perhaps by biasing the recruitment of task-relevant information (which might be lateralized). Our task would seem to draw heavily on this latter component. Future research could be designed to more directly explore these hypotheses.

Fourth, we manipulated the neural activity of the DLPFC in order to emphasize its role in language control. However, we did not target classic language areas (Broca's or Wernicke's area). In order to further understand the top-down modulation effect of the DLPFC over language comprehension it is vital to make such comparisons, as well as employ manipulations and measures that can assess functional connectivity. For example, unilateral stimulation of the left DLPFC and the Wernicke's area can further expand our knowledge regarding top-down control in language comprehension. Finally, the present study sought to explore the influence of motivational factors on language comprehension thorough the mediation of cognitive control factors. However, we relied on self-report measures of approach motivation. Future research can examine how trait motivation drives or interacts with state motivation to influence cognitive control over language comprehension.

5. Conclusions

The results of the current study demonstrate how altering the balance between the two cerebral hemispheres influences performance on a semantic judgment task. Idioms present an ideal task context given their variation in predictability and degree of semantic relatedness. We suggest that the effects of tDCS over DLPFC reflect changes in top-down influences on semantic processes, pointing to a general way in which this region is used to predict and regulate task-relevant information. In addition, the results point to how motivation variables may modulate cognitive control functions and influence the use of task-relevant information. Idiom comprehension can serve as a useful platform to understand how cognitive control influences language comprehension.

Acknowledgments

This study was supported by a BSF Grant 2007184 awarded to RI and ML, an ERC starting grant (Inspire 200512), and an ISF (Grant 100/10) awarded to ML.

The authors would like to thank the anonymous reviewers for their valuable comments and suggestions to improve the paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.neuropsychologia.2012.05.031.

References

Banich, M. T., Milham, M. P., Atchley, R. A., Cohen, N. J., Webb, A., Wszalek, T., et al. (2000). Prefrontal regions play a predominant role in imposing an attentional 'set': Evidence from fMRI. *Cognitive Brain Research*, *10*(1–2), 1–9.

Bar, M. (2007). The proactive brain: Using analogies and associations to generate predictions. *Trends in Cognitive Sciences*, *11*(7), 280–289.

Bar, M. (2009). The proactive brain: Memory for predictions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1521), 1235–1243.

Beeman, M. J., & Bowden, E. M. (2000). The right hemisphere maintains solution-related activation for yet-to-be-solved problems. *Memory & Cognition*, *28*(7), 1231–1241.

Berkman, E. T., & Lieberman, M. D. (2009). Approaching the bad and avoiding the good: Lateral prefrontal cortical asymmetry distinguishes between action and valence. *Journal of Cognitive Neuroscience*, *22*(9), 1970–1979.

Blair, I. V., Urland, G. R., & Ma, J. E. (2002). Using Internet search engines to estimate word frequency. *Behavior Research Methods, Instruments, & Computers*, *34*(2), 286–290.

Boggio, P. S., Khoury, L. P., Martins, D. C., Martins, O. E., de-Macedo, E. C., & Fregni, F. (2009). Temporal cortex direct current stimulation enhances performance on a visual recognition memory task in Alzheimer disease. *Journal of Neurology, Neurosurgery & Psychiatry*, *80*, 444–447.

Bowden, E. M., & Jung-Beeman, M. (2003). Aha! Insight experience correlates with solution activation in the right hemisphere. *Psychonomic Bulletin & Review*, *10*(3), 730–737.

Bubic, A., von Cramon, D. Y., & Schubotz, R. I. (2010). Prediction, cognition and the brain. *Frontiers in Human Neuroscience*, *4*, 1–15.

Cacciari, C., & Glucksberg, S. (1991). Understanding idiomatic expressions: The contribution of word meanings. In G. B. Simpson (Ed.), *Understanding word and sentence* (pp. 217–240). Amsterdam: North-Holland.

Cacciari, C., & Tabossi, P. (1988). The comprehension of idioms. *Journal of Memory and Language*, *27*, 668–683.

Canal, P., Vespignani, F., Molinaro, N., & Cacciari, C. (2010). Anticipatory mechanisms in idiom comprehension: Psycholinguistic and electrophysiological evidence. In M. Balconi (Ed.), *Neuropsychology of communication* (pp. 131–144). Milan: Springer.

Carver, C. S., & White, T. L. (1994). Behavioral inhibition, behavioral activation, and affective responses to impending reward and punishment: The BIS/BAS scales. *Journal of Personality and Social Psychology*, *67*, 319–333.

Coan, J. A., & Allen, J. J. B. (2003). Frontal EEG asymmetry and the behavioral activation and inhibition systems. *Psychophysiology*, *40*(1), 106–114.

DeLong, K. A., Urbach, T. P., & Kutas, M. (2005). Probabilistic word pre-activation during language comprehension inferred from electrical brain activity. *Nature Neuroscience*, *8*(8), 1117–1121.

Fecteau, S., Pascual-Leone, A., Zald, D. H., Liguori, P., Theoret, H., Boggio, P. S., et al. (2007). Activation of prefrontal cortex by transcranial direct current stimulation reduces appetite for risk during ambiguous decision making. *Journal of Neuroscience*, *27*(23), 6212–6218.

Fertonani, A., Rosini, S., Cotelli, M., Rossini, P. M., & Miniussi, C. (2010). Naming facilitation induced by transcranial direct current stimulation. *Behavioural Brain Research*, *208*(2), 311–318.

Flöel, A., Rösser, N., Michka, O., Knecht, S., & Breitenstein, C. (2008). Noninvasive brain stimulation improves language learning. *Journal of Cognitive Neuroscience*, *20*(8), 1415–1422.

Fogliata, A., Rizzo, S., Reati, F., Miniussi, C., Oliveri, M., & Papagno, C. (2007). The time course of idiom processing. *Neuropsychologia*, *45*(14), 3215–3222.

Fregni, F., Boggio, P. S., Nitsche, M., Bermpohl, F., Antal, A., Feredoes, E., et al. (2005). Anodal transcranial direct current stimulation of prefrontal cortex enhances working memory. *Experimental Brain Research*, *166*(1), 23–30.

Fruchtman, M., Ben-Nathan, O., & Shani, N. (2001). *Arial dictionary of idioms*. Israel: Korim Ltd.

Gandiga, P. C., Hummel, F. C., & Cohen, L. G. (2006). Transcranial DC stimulation (tDCS): A tool for double-blind sham-controlled clinical studies in brain stimulation. *Clinical Neurophysiology*, *117*(4), 845–850.

Gray, J. A. (1987). The neuropsychology of emotion and personality. In S. M. Stahl, S. D. Iverson, & E. C. Goodman (Eds.), *Cognitive neuropsychology* (pp. 171–190). New York: Oxford University Press.

Gray, J. A., & McNaughton, N. (2000). *The neuropsychology of anxiety: An enquiry into the functions of the septo-hippocampal system* (2nd ed.). New York: Oxford University Press.

Harmon-Jones, E., & Allen, J. J. (1997). Behavioral activation sensitivity and resting frontal EEG asymmetry: Covariation of putative indicators related to risk for mood disorders. *Journal of Abnormal Psychology*, *106*(1), 159–163.

Hecht, D., Walsh, V., & Lavidor, M. (2010). Transcranial direct current stimulation facilitates decision making in a probabilistic guessing task. *Journal of Neuroscience*, *30*(12), 4241–4245.

Iyer, M. B., Mattu, U., Grafman, J., Lomarev, M., Sato, S., & Wassermann, E. M. (2005). Safety and cognitive effect of frontal DC brain polarization in healthy individuals. *Neurology*, *64*(5), 872.

Jimura, K., Locke, H. S., & Braver, T. S. (2010). Prefrontal cortex mediation of cognitive enhancement in rewarding motivational contexts. *Proceedings of the National Academy of Sciences*, *107*(19), 8871–8876.

Jung-Beeman, M. (2005). Bilateral brain processes for comprehending natural language. *Trends in Cognitive Sciences*, *9*(11), 512–518.

Jung-Beeman, M., Bowden, E. M., Haberman, J., Frymiare, J. L., Arambel-Liu, S., Greenblatt, R., et al. (2004). Neural activity when people solve verbal problems with insight. *PLoS Biology*, *2*(4), E97.

Kan, I. P., & Thompson-Schill, S. L. (2004). Selection among perceptual and conceptual representations. *Cognitive, Affective, & Behavioral Neuroscience*, *4*(4), 466–482.

Kincses, T. Z., Antal, A., Nitsche, M. A., Bartfai, O., & Paulus, W. (2004). Facilitation of probabilistic classification learning by transcranial direct current stimulation of the prefrontal cortex in the human. *Neuropsychologia*, *42*(1), 113–117.

Koechlin, E., Ody, C., & Kouneiher, F. (2003). The architecture of cognitive control in the human prefrontal cortex. *Science*, *302*(5648), 1181–1185.

Kutas, M., & Federmeier, K. D. (2000). Electrophysiology reveals semantic memory use in language comprehension. *Trends in Cognitive Sciences*, *4*(12), 463–470.

Lauro, L. J., Tettamanti, M., Cappa, S. F., & Papagno, C. (2008). Idiom comprehension: A prefrontal task? *Cerebral Cortex*, *18*(1), 162–170.

MacDonald, A. W., III, Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science*, *288*(5472), 1835–1838.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Neuroscience*, *24*(1), 167.

Miyashita, Y. (2004). Cognitive memory: Cellular and network machineries and their top-down control. *Science*, *306*(5695), 435.

Nitsche, M. A., & Paulus, W. (2000). Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *Journal of Physiology*, *527*(3), 633.

Nitsche, M. A., & Paulus, W. (2001). Sustained excitability elevations induced by transcranial DC motor cortex stimulation in humans. *Neurology*, *57*(10), 1899.

Nitsche, M. A., Schauenburg, A., Lang, N., Liebetanz, D., Exner, C., Paulus, W., et al. (2003). Facilitation of implicit motor learning by weak transcranial direct current stimulation of the primary motor cortex in the human. *Journal of Cognitive Neuroscience*, *15*(4), 619–626.

Nunberg, G., Sag, I. A., & Wasow, T. (1994). Idioms. *Language*, *70*, 491–538.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*(1), 97–113.

Oliveri, M., Romero, L., & Papagno, C. (2004). Left but not right temporal involvement in opaque idiom comprehension: A repetitive transcranial magnetic stimulation study. *Journal of Cognitive Neuroscience*, *16*, 848–855.

Papagno, C. (2010). Idiomatic language comprehension: Neuropsychological evidence. In M. Balconi (Ed.), *Neuropsychology of communication* (pp. 111–129). Milan: Springer.

Pessoa, L. (2008). On the relationship between emotion and cognition. *Nature Reviews Neuroscience*, *9*(2), 148–158.

Pessoa, L. (2009). How do emotion and motivation direct executive control? *Trends in Cognitive Sciences*, *13*(4), 160–166.

Pickering, A. D., & Gray, J. A. (1999). The neuroscience of personality. In L. A. Pervin, & O. P. John (Eds.), *Handbook of personality: Theory and research* (2nd ed.). New York: Guilford Press.

Pizzagalli, D. A., Sherwood, R. J., Henriques, J. B., & Davidson, R. J. (2005). Frontal brain asymmetry and reward responsiveness: A source-localization study. *Psychological Science*, *16*(10), 805–813.

Proverbio, A., Crotti, C., Zani, A., & Adorni, R. (2009). The role of left and right hemispheres in the comprehension of idiomatic language: An electrical neuroimaging study. *BMC Neuroscience*, *10*(1), 116, http://dx.doi.org/10.1186/1471-2202-10-116.

Rizzo, S., Sandrini, M., & Papagno, C. (2007). The dorsolateral prefrontal cortex in idiom interpretation: An rTMS study. *Brain Research Bulletin*, *71*(5), 523–528.

Roehm, D., Bornkessel-Schlesewsky, I., Rosler, F., & Schlesewsky, M. (2007). To predict or not to predict: Influences of task and strategy on the processing of semantic relations. *Journal of Cognitive Neuroscience*, *19*(8), 1259–1274.

Romani, C., Ward, J., & Olson, A. (1999). Developmental surface dysgraphia: What is the underlying cognitive impairment? *The Quarterly Journal of Experimental Psychology*, *52*(1), 97–128.

Rosenthal, R. (2009). *Dictionary of Hebrew idioms and phrases*. Israel: Keter Books Ltd.

Savine, A. C., & Braver, T. S. (2010). Motivated cognitive control: Reward incentives modulate preparatory neural activity during task-switching. *Journal of Neuroscience*, *30*(31), 10294–10305.

Spielberg, J. M., Miller, G. A., Engels, A. S., Herrington, J. D., Sutton, B. P., Banich, M. T., et al. (2011). Trait approach and avoidance motivation: Lateralized neural activity associated with executive function. *Neuroimage*, *54*(1), 661–670.

Sutton, S. K., & Davidson, R. J. (1997). Prefrontal brain asymmetry: A biological substrate of the behavioral approach and inhibition systems. *Psychological Science*, *8*(3), 204.

Titone, D. A., & Connine, C. M. (1994). Comprehension of idiomatic expressions: Effects of predictability and literality. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *20*(5), 1126–1138.

Titone, D. A., & Connine, C. M. (1999). On the compositional and noncompositional nature of idiomatic expressions. *Journal of Pragmatics.*, *31*, 1655–1674.

van Steenbergen, H., Band, G. P., & Hommel, B. (2009). Reward counteracts conflict adaptation. Evidence for a role of affect in executive control. *Psychological Science*, *20*(12), 1473–1477.

Vespignani, F., Canal, P., Molinaro, N., Fonda, S., & Cacciari, C. (2009). Predictive mechanisms in idiom comprehension. *Journal of Cognitive Neuroscience*, *22*(8), 1682–1700.

Zempleni, M. Z., Haverkort, M., Renken, R., & Stowe, A. L. (2007). Evidence for bilateral involvement in idiom comprehension: An fMRI study. *Neuroimage*, *34*(3), 1280–1291.