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# Enhancing cognitive control components of insight problems solving by anodal tDCS of the left dorsolateral prefrontal cortex

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*Background:* Executive functions play a vital role in semantic processing. Recently, transcranial direct current stimulation (tDCS) over frontal regions associated with cognitive control has been found to enhance verbal insight problem solving. The aim of the current study was to extend our understanding of the cognitive control processes modulating verbal insight problem solving.
*Hypotheses:* Anodal stimulation over the left Dorsolateral Prefrontal Cortex (DLPFC) was predicted to improve performance in solving insight problems. Particularly, it was expected that this effect would be focused on solution recognition, which is hypothesized to be directly related to control processes, and would be more pronounced for difficult problems, hypothesized to require more cognitive demand. Moreover, we predicted that this effect would be modulated by approach motivation tendencies, due to cognition and motivation interactions in the DLPFC.
*Methods:* 21 participants performed a verbal insight problem task twice, once under active anodal tDCS over the left DLPFC and once under sham stimulation, with a one week interval between sessions. Participants had 7 s to generate a solution for each problem, and then were requested to indicate whether a target word was the correct solution or not.
*Results:* Stimulation significantly enhanced solution recognition for difficult problems. This effect was modulated by trait motivation, i.e. was larger for participants with lower approach motivation. No effects were found for easy problems, or solution generation.
*Conclusions:* Left DLPFC executive control modulates semantic processing of verbal insight problems. The observed synergy between language, cognition and motivation carries theoretical implication as well as practical consideration for future stimulation research.



## Introduction

Language processing and comprehension encompasses linguistic processes as well as non-linguistic processes. For instance, solving verbal insight problems requires one to perform multiple complex cognitive operations that involve language comprehension, semantic processing and problem solving [1]. Previous studies have investigated the semantic aspects of this ability, demonstrating extensive involvement of a temporal bilateral network, with a right hemisphere (RH) prevalence when solving verbal problems with insight [2–4]. However, the role of executive functions associated with the problem solving aspects of this ability has received less research attention.

Cerruti and Schlaug [5] were able to enhance performance of verbal problem solving with the use of a non-invasive stimulation of the left DLPFC (Brodmann's Area 9/46), a brain area associated with executive and cognitive control, and provided vital evidence for the importance of this region in supporting the processing of verbal insight problems. However, the nature of the neuro-cognitive processes underlying the DLPFC support in solving verbal insight problems remained unclear. The main aim of the current study was to further explore the role of the DLPFC in solving verbal insight problems, and in particular, to advance our understanding regarding the cognitive control components mediating the stimulation effect and the conditions in which cognitive control operations are required in order to promote solving these problems.

A common paradigm designed to investigate the neural correlates of verbal insight problem solving is based on the Compound Remote Associates (CRA) set of problems [4,6,7]. Each item in the set consists of three prime words, each joins the target word to form a compound word or a two-word phrase, (e.g. AGE/MILE/

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SAND form the compounds STONE-AGE, MILESTONE, and SANDSTONE with the solution word STONE). To solve a problem, one usually has to overlook the most accessible, salient associations, and creatively think of distantly related information which is more likely to lead to the correct solution.

Accumulated findings from behavioral and imaging studies, employing different methodological variations of this paradigm have shown converging evidence for a dominant involvement of the RH [2,3]. These consistent findings are in line with the predictions of the BAIS model for semantic processing [8], namely that temporal sites in the RH will have unique involvement when distant meanings are activated and integrated.

In addition to the cortical activity attributed to the RH involvement in semantic processing, solving the CRA items also invokes activity that has been attributed to processes related to general problem solving [3]. The hypothesis that executive functions are likely to be involved in solving these complex verbal problems, beyond their semantic aspects, is further supported by two studies demonstrating cognitive control modulation of the semantic processes involved in this task [5,9].

Cognitive control is a construct which incorporates aspects of different high order processes that enable the formation, maintenance, and updating of behavioral goal representations [10], as well as top–down biasing of other mechanisms that enhance or inhibit information processing [11–13]. Previous studies have associated cognitive control with neural activity in the DLPFC [14,15] and the anterior cingulate cortex (ACC) [10,16].

Few studies of semantic processing have described cognitive control contribution to language processing, mediated by the PFC, using other semantic tasks. For instance, neuroimaging studies have attributed the activation of regions within the left PFC during semantic processing to the recruitment of semantic memory systems [17,18]. Further evidence for the crucial role that the left DLPFC plays in executive control over semantic processing, converges in various idiom comprehension studies using imaging, brain stimulation and brain damaged patients. In particular the DLPFC has been found to be involved in meaning retrieval from semantic memory, selection between alternative meanings and suppression of irrelevant information [19,20].

Cerruti and Schlaug [5] recently provided evidence for DLFPC involvement in processing verbal insight problems, but the underlying processes facilitating this involvement have not yet been described. The authors demonstrated that stimulation of the left DLPFC with transcranial direct current stimulation (tDCS) enhanced performance in solving CRA problems. In particular, they found that when given 30 s to solve CRA problems, subjects solved more problems after anodal tDCS to the left DLPFC, but not to the right DLPFC, as compared with sham stimulation. Moreover, participants generated less wrong solutions following left DLPFC stimulation compared to the sham condition. Taken together, these results indicate that stimulating the left DLPFC not only led to increased fluency in solutions generation, but also to improved solution selection. Notably, stimulation did not affect performance in a simple verbal fluency task. The authors argued that the enhancement in the more complex CRA task was facilitated by neural networks associated with executive functions [5].

These findings prompt interesting questions regarding the role of cognitive control and the left DLPFC in solving verbal insight problems. Aiming to better describe the underlying neuro-cognitive processes that modulate verbal problem solving enhancement, we created a stimulation study with few methodological modifications compared to the procedure used by Cerruti and Schlaug's [5].

First, in order to probe solution recognition separately from solution generation, a different methodological variation of the CRA paradigm was used. Following a procedure used by Bowden & Jung-Beeman [6,7], participants were presented with the problem words for a shorter duration of time, and then presented with a target word. Participants were requested to solve the problem while the prime words were presented, and indicate whether the target word was the correct solution or not. The time limit for solution, while the words were still presented, was set to 7 s, following Jung-Beeman and Bowden [2].

This procedure places less emphasis on solution generation, which is assumed to be more related to semantic processing, and more emphasis on solution recognition, which may require executive control elements that may be supported by the DLPFC. Distinguishing between the processes enabled sensitive exploration of the specific processes that are being modulated by anodal tDCS over the left DLPFC. We predicted that modulation of cognitive control would result in better recognition of the solutions, rather than generating more creative solutions in the shortened time frame.

Second, in order to better characterize the instances in which cognitive control is more needed, we divided the items by difficulty. We addressed level of complexity directly, by using two difficulty levels of CRA problems, to allow a sensitive examination of the hypothesis that higher complexity demands more involvement of executive functions supported by the DLPFC. We predicted that top–down control over semantic processes would be enhanced during activation of the left DLPFC, leading to improvement mainly in the more difficult problems.

Finally, we introduced trait motivation as a possible moderator of the stimulation effect. It has been argued that motivational variables might interact with executive functions, and cognitive control in particular, to influence the prioritization of behavioral goals [21,22]. Two reasons led us to believe that stimulating the left DLPFC might modulate interaction between motivation and cognitive control. First, neuroimaging and EEG studies have linked approach related motivations to frontal regions of the left hemisphere: The Behavioral Approach System (BAS), which regulates responses to rewarding stimuli [23–25], has been linked to the LH [26] and its frontal regions in particular [27–29]. Second, recent neuroimaging evidence suggests that the left DLPFC serves as a key neural locus for the integration of cognitive and motivational information [12]. Thus, we hypothesized that individual motivational tendencies related to trait approach motivation might moderate tDCS effects on executive control components of the given task. We used the BIS/BAS scales [30] to measure trait motivation level, and predicted that individual variation on the BAS scale would influence performance changes induced by tDCS in task performance.

In summary, the present study aimed to extend our understanding of the cognitive control processes modulating verbal insight problem solving by targeting specific processes that could be enhanced by stimulation and by assessing the effect of increased load on this enhancement together with its possible modulation by approach motivation. We predicted that anodal stimulation over the left DLPFC would improve performance in the CRA compared to sham stimulation. Particularly, it was expected that this effect would be restricted to solution recognition, which is hypothesized to be directly related to control processes, and would be more pronounced for difficult problems, hypothesized to require more cognitive efforts. Moreover, we predicted that this effect would be modulated by BAS tendencies, due to cognition and motivation interactions in the DLPFC.

## Methods

### *Participants*

Twenty one students (11 female) participated after giving their 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). All were right handed, as assessed by the Edinburgh Handedness inventory [31], native Hebrew speakers, and free from any history of psychiatric or neurological disorders. Their sight was normal or corrected to normal, and their age ranged from 18 to 29 years ($M = 23.1$, SD $= 2.5$).

*Experimental design*

A 2 × 2 within-subject design was employed, with stimulation condition (anodal over left DLPFC/sham) and difficulty level of the insight problem (easy or difficult) as the within-subjects factors. Difficulty level was defined by rate of early, spontaneous solution to the problem as measured in pilot experiments [32]. The BAS/BIS motivational trait scores were correlated with performance in the different conditions.

*Materials*

*Verbal insight problems – CRA task*

48 items were taken from a set of 176 CRA problems in Hebrew, developed and validated in a pilot study [32]. Each problem contained three prime words, and a solution word that joins each of the prime words to create a familiar phrase. For half of the problems, an unrelated distractor word, equal in length to the solution word, was matched.

The items were selected based on their difficulty level. Difficulty level was determined in a pilot testing ($n = 28$), and defined as rate of participants who solved the problem in a limited time frame. In the pilot test, participants were presented with each problem for 4 s, and requested to attempt to solve the problems, and indicate reaching a solution with a button press. Display of problem words was identical in its characteristics to the display in the current study.

The prior solution rates of the item subset ranged between 3.7 and 37.5%. Difficult items were solved by less than 11.3% of the participants during the limited time, while easy items were solved by a rate higher than 11.3% of the participants. Two lists of 24 items were composed; each list contained 12 easy and 12 difficult items. The lists did not differ in difficulty level ($F < 1$).

*Assessment of motivation – BIS/BAS scales*

Trait motivation was assessed using the BIS/BAS scales [30]. The questionnaire includes 24 items (4 fillers). 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 a behavioral inhibition measure (BIS; based on 7 items, e.g. "I worry about making mistakes") and three behavioral approach measure (BAS) subscales: BAS Reward Responsiveness (positive anticipation of rewarding events, e.g. "When I see an opportunity for something I like I get excited right away"), BAS Drive (rewards pursuit) and BAS Fun Seeking (search for new rewarding situations). BAS scale is calculated as sum of scores in the 13 items composing these subscales.

*tDCS*

A direct current of 1 mA for up to 11 min was induced by two saline-soaked surface sponge electrodes (35 $cm^2$) and delivered by a battery-driven, constant-current stimulator (Rolf Schneider Electronics, Germany). The current had a ramp-up time of 30 s, was held at 1 mA for 5 min until the beginning of the experimental task, and until the completion of the experimental task (6 additional minutes at most), and then ramped down over 30 s.

There was one active unilateral condition and one sham condition. In the anodal unilateral condition, the anode electrode was placed over the left DLPFC and the cathode electrode was placed over the contralateral orbitofrontal cortex. Localization was established using a 10–20 EEG technique, in which F3 was identified as left DLPFC area, following Cerruti and Schlaug [5]. We used the orbitofrontal cortex (FP2) as a reference electrode relying on evidence that patients with orbitofrontal cortex lesions show intact performance in semantic tasks [33]. In the sham condition, the electrodes were placed at the same position as the unilateral anodal stimulation; however, the current intensity was turned off automatically after 30 s. Therefore, during sham stimulation, the subjects felt the initial itching sensation in the beginning, but received no current for the rest of the stimulation period [34].

*Procedure*

Each participant completed 2 identical experimental sessions separated by one week. In each session a different stimulation condition was applied, and a different stimulus list was used. The order of stimulus conditions, as well as stimulus list, was counterbalanced across participants. Additionally, at the beginning of the first session, participants completed the BIS/BAS scales. Apart from being conducted under anodal or sham stimulation, the task and procedure replicated the previous studies with the English CRA version [7].

The participants were comfortably seated in a quiet 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 5 practice trials in which they received feedback for their response. Following a short debrief, the stimulation experiment began. After 5 min of stimulation, the subjects performed the experimental task, including 24 trials without feedback.

In each trial, participants were presented with the three prime words for 7 s, which served as a time limit for early solution. During this time limit, the participants were asked to solve the problem. After a solution was indicated by a button press, or the time limit was exceeded, a target word was presented. The participants were instructed to indicate by a button press whether the target word was the correct solution of the problem, or not. On half of the trials, the target was the correct solution word, and on the other half- an unrelated distractor (see Fig. 1).

*Statistical analysis*

The analyses were conducted using SPSS software package (version 15.0, Chicago, IL). Repeated measures analysis of variance (ANOVA) was used to analyze the effect of 2 within-subjects factors (stimulation and difficulty) on each of two performance measures, that served as dependent variables in two separate analyses: 1) early solution rate, the percentage of problems solved within the 7 s, a measure for solution generation; 2) accuracy rate, the percentage of accurate responses to the target word, a measure for solution recognition. Bonferroni correction for multiple comparisons was used to further analyze significant interactions.

In order to describe the non-linear relation between BAS scores and individual improvement in solving the problems following the stimulation, Spearman rank–order correlation coefficient (Spearman's rho) was used. The individual improvement score was calculated by subtracting the performance score in the sham condition from the active condition score. To control for changes in baseline, the delta was then divided by the performance score in the sham condition. Positive scores in the individual improvement score represent an improvement in performance following stimulation, whereas negative scores on this scale represent a decline in performance.

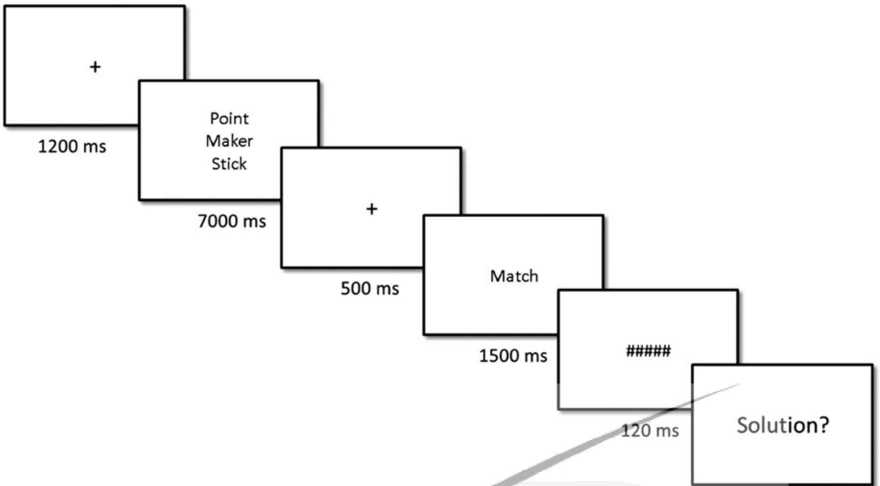


**Figure 1.** Sequence and timing of events within each trial. Each trial began with a central fixation cross, presented for 1200 ms. The three prime words were then presented simultaneously, above, at and below the center of the screen. The words remained on the screen for 7 s, during which the participants were asked to solve the problem. After a solution was indicated, or the time limit was exceeded, a fixation cross re-appeared for an additional 500 ms, followed by a presentation of the target word for 1500 ms. Then, the word "Solution?" appeared on the screen, and the participants were instructed to indicate whether the target word was the correct solution of the problem, or not. On half of the trials, the target was the correct solution word, and on the other half- an unrelated distractor. In this example, the correct solution followed the three problem words.

## Results

Solution generation was analyzed using a 2 × 2 repeated measures ANOVA, with difficulty (easy/hard) and stimulation (active/sham) as within-subject factors, and early solution rates as the dependent variable. A predicted difficulty effect was found, $F(1,20) = 56.907$, $P < 0.001$, $e^2 = 0.74$, validating the difficulty classification: average solution rate was only 8.91% ($SE = 3.13$) for the difficult problems, and 28.44% ($SE = 3.94$) for the easy problems. However, stimulation did not have an effect on the rate of problems solved within the 7 s limit, nor did it interact with difficulty ($F < 1$, see Fig. 2). Thus, in the short solution time limit, no stimulation effect on solution generation was observed.

In order to test stimulation effect on solution recognition, a similar analysis was performed, with accuracy rates as the dependent variable. The ANOVA revealed a significant interaction between stimulation and item difficulty, $F(1,20) = 14.452$, $P = 0.001$, $e^2 = 0.42$. Paired samples $t$-tests discovered the interaction source in a significant stimulation advantage in difficult items, $t(20) = 3.587$, $P = 0.002$, but not in easy items, $t(20) = 0.982$, $P = 0.338$. Thus, according to our predictions, stimulation only benefited difficult problems. Stimulation had no significant main effect on accuracy, $F(1,20) = 2.134$, $P = 0.16$, nor did difficulty ($F < 1$). Mean accuracy rates and standard errors are presented in Fig. 3.

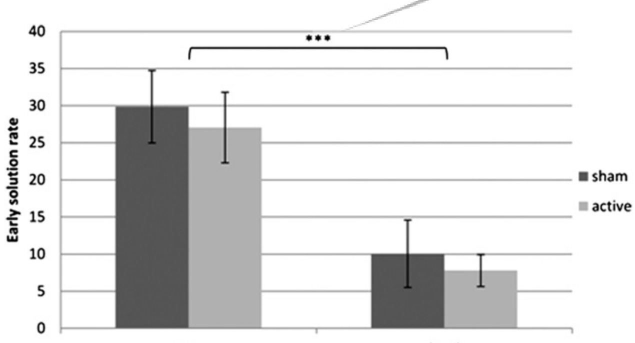


**Figure 2.** Solution generation: mean early solution rates and SE, by stimulation condition and item difficulty. ***$P < 0.001$.

In order to characterize the stimulation effect found on recognizing solutions for difficult items, level of individual improvement in solving difficult problems following stimulation was calculated (see statistical analyses). Then, a spearman correlation was used to evaluate the predicted relation between stimulation effect magnitude and motivation. Aligned with our predictions, a significant correlation was found between BAS scores and improvement in difficult items, Spearman's rho = 0.492, $P = 0.023$, so that participants with higher BAS scores, reflecting a lower tendency for motivation approach [30], benefited more from the stimulation. It is notable that no correlation was found between BAS scores and the magnitude of stimulation induced change in easy items (calculated in a similar fashion), Spearman's rho = 0.328, $P = 0.146$.

## Discussion

In line with our predictions, we found that anodal tDCS over the left DLPFC enhanced solution recognition for difficult problems, and that this effect was modulated by trait motivation, i.e. was larger for participants with lower approach motivation. These findings advance our understanding regarding the conditions in which cognitive control operations are required in order promote complex verbal insight problems, and attest to DLPFC support of these cognitive processes.

Contrary to Cerruti and Schlaug's [5] report on solution generation enhancement following anodal left DLPFC stimulation (when participants were given up to 30 s for generating a solution), in the current study, when only 7 s were allowed for solving each problem, anodal stimulation over the left DLPFC did not enhance solution generation, while solution recognition for hard problems was improved. The dissociation found between solution recognition and solution generation in the short time frame for solutions, sheds more light on the specific processes enhanced by stimulation. When trying to generate a solution, activation of various distant meanings related to the prime words is required in order to find an indirect connection, a forth word, that connects all the dots. Thus, solution generation is highly dependent on complex semantic processing, which is mainly supported by RH temporal activations [3]. Previous studies that measured solution recognition after failing to generate solutions, demonstrated that recognition also

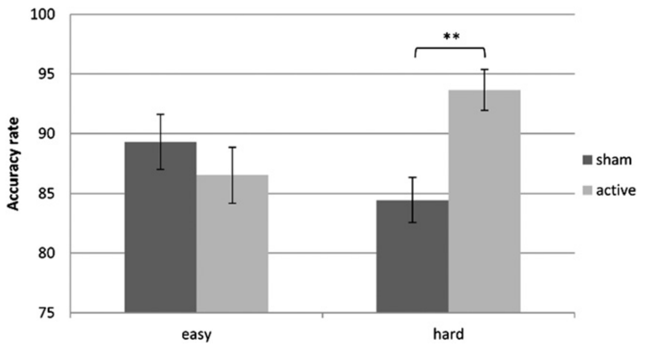


**Figure 3.** Solution recognition: mean accuracy rates and SE, by stimulation condition and item difficulty. $^{**}P < 0.01$.

relies on semantic processing, as it utilizes the availability of solution-related information in the RH [1,6]. However, these studies were unable to determine whether the ability to recognize a solution when encountered, before generating it self-reliantly, is due to semantic properties, i.e. low activation of the solution word- too weak to allow the solvers to generate a solution, or due to executive properties, i.e. inability to recruit control mechanisms to disengage from a stronger activation [6]. The current study demonstrated that solution recognition could be enhanced without effecting solution generation, implying that left DLPFC enhancement was focused on DLPFC-characteristic control mechanisms involved in recognition, which may represent the enhancement of top–down control over semantic processes, but did not boost the semantic activation per-se, as those are shared by both generation and recognition.

In later stages of processing, following further semantic processing, it could be postulated that the same control mechanisms underlying the ability to recognize the solution (and to recognize an incorrect solution, when prompted), allows the solver to overlook incorrect solution alternatives, and finally reach the correct one. This hypothesis is supported by Cerruti and Schlaug's findings [5]: when participants were given more time to generate a solution, stimulation of the left DLPFC enhanced solution generation expressed as more correct solutions reported, as well as less incorrect solutions.

The targeted stimulation effect on the difficult problems indicates that DLPFC excitation is indeed related to cognitive control processes, which are more called for when the cognitive demand is higher. This finding reinforces the preliminary evidence reported by Cerruti and Schlaug [5], who demonstrated dissociation in the stimulation effect on insight problem solving and a simple verbal fluency task. The authors attributed the dissociation to the level of complexity, and presented this as evidence that cognitive control was modulated, assuming higher complexity demands more involvement of executive functions. However, while both tasks share components of verbal memory, they differ in many other aspects above and beyond the level of complexity. Thus, the current finding provides more direct evidence for cognitive control mediation of the stimulation effect.

Taken together, the targeted stimulation effect on solution recognition of difficult problems, as opposed to null effects on recognition of solutions for easy items, or solution generation within the short time frame, distinguishes between the linguistic and non-linguistic processes underlying insight problem solving. This suggests that the modulation of insight problem solving by stimulation of the left DLPFC was mediated by control processes, rather than semantic processes. These findings provide evidence that LH cognitive control mechanisms modulate linguistic processing, and add to the preliminary evidence reported for executive control associated regions involvement in semantic processing [17,18,20]. Future investigations could further explore this enhancement at the neural level, and describe the nature of the excitatory stimulation effect on cognitive control processes in the left DLPFC, particularly whether the stimulation effect was mediated by inhibitory or excitatory operations.

Along with our observation that left DLPFC stimulation enhanced the cognitive control modulation of insight problem solving, our results also point to a moderation of this effect by motivation. Individuals with lower tendency for approach motivation exhibited more improvement in recognizing solutions for difficult problems following the stimulation, hence benefited more from the stimulation. Considering previous reports on moderation of left DLPFC neural activity by trait approach motivation [35,36], it could be postulated that the stimulation enhanced neural activity in this region in particularly for individuals who otherwise would experience lower activation in that region. Recently, another study examining cognitive control over semantic processing of idioms, established that motivation trait scores, as measured by BIS/BAS scale, moderated the effect of tDCS over the DLPFC on idiom comprehension [20]. These findings converge and clearly point toward impact of trait motivation on cognitive control, and in particular the top–down regulation of semantic processing.

The importance of motivation in the cognitive domain [21,37,38] and especially its ability to moderate stimulation effects on control over language processing, as revealed here, suggests interesting potential for the enhancement of cognitive functions. For instance, future studies could explore effects of situational enhancement in motivation on complex cognitive tasks that heavily rely on effective cognitive control. Moreover, monitoring motivational aspects in stimulation studies and clinical applications may provide a useful measure for identifying individuals who could benefit more from the stimulation. In conjunction with the applied research, theoretical elaboration of the hypothesis regarding cognitive control mediated influence of trait motivation on language processing could be extremely valuable.

In conclusion, by using sensitive examination of stimulation effects on insight problem solving, our study presents substantial evidence for the importance of left hemisphere cognitive control mechanisms in language processing. Specifically, we have shown that left DLPFC related executive functions contribute to the ability to recognize a solution for complex verbal problems when encountered. Presumably, this ability later assisted the solvers to reach a solution on their own, by modulating the semantic processes and allowing them to recognize incorrect solutions and select the correct ones. We have also observed that stimulation effect on cognitive control over linguistic processes is moderated by motivation, showing a complex synergy in the contribution of non-linguistic affective and cognitive processes to language processing and comprehension. Future studies could deepen our understanding of this complex synergy by exploring the connectivity between the DLFPC and regions associated with semantic processing as well as reward sensitive regions. Moreover, future studies could further explore the potential of enhancing semantic processing by stimulating both verbal and non-verbal regions.

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