Published in final edited form as:
Brain Stimul. 2014 ; 7(6): 773–783. doi:10.1016/j.brs.2014.10.003.

The uncertain outcome of prefrontal tDCS

Sara Tremblay[1,2], **Jean-François Lepage**[3], **Alex Latulipe-Loiselle**[1,2], **Felipe Fregni**[3], **Alvaro Pascual-Leone**[4], and **Hugo Théoret**[1,2]

[1]Psychology, University de Montreal

[2]Research Center, Centre Hospitalier Universitaire de l'Hôpital Sainte-Justine

[3]Neuromodulation laboratory, Spaulding Rehabilitation Hospital, Harvard Medical School

[4]Berenson Allen Center for Non-Invasive Brain Stimulation, Beth Israel Deaconess Medical Center, Harvard Medical School

Abstract

Background—Transcranial direct current stimulation (tDCS) is increasingly used in research and clinical settings, and the dorsolateral prefrontal cortex (DLPFC) is often chosen as a target for stimulation. While numerous studies report modulation of cognitive abilities following DLPFC stimulation, the wide array of cognitive functions that can be modulated makes it difficult to predict its precise outcome.

Objective—The present review aims at identifying and characterizing the various cognitive domains affected by tDCS over DLPFC.

Methods—Articles using tDCS over DLPFC indexed in PubMed and published between 2000 and January 2014 were included in the present review.

Results—tDCS over DLPFC affects a wide array of cognitive functions, with sometimes apparent conflicting results.

Conclusion—Prefrontal tDCS has the potential to modulate numerous cognitive functions simultaneously, but to properly interpret the results, a clear a priori hypothesis is necessary, careful technical consideration are mandatory, further insights into the neurobiological impact of tDCS are needed, and consideration should be given to the possibility that some behavioral effects may be partly explained by parallel modulation of related functions.

Keywords

transcranial direct current stimulation; neurostimulation; cognition; executive functions; dorsolateral prefrontal cortex; state-dependency; review

Corresponding author: Hugo Théoret, PhD, Département de Psychologie, Université de Montréal, CP 6128, Succ. Centre-Ville, Montréal, QC, Canada, H3C 3J7, Tel: 514-343-6362, Fax: 514-343-5787, hugo.theoret@umontreal.ca.

Conflict of Interest Disclosure: APL serves on the scientific advisory boards for Nexstim, Neuronix, Starlab Neuroscience, Neuroelectrics, Axilum Robotics, Magstim Inc., and Neosync; and is listed as an inventor on several issued and pending patents on the real-time integration of transcranial magnetic stimulation (TMS) with electroencephalography (EEG) and magnetic resonance imaging (MRI).

Introduction

In 1865, Broca introduced the idea of studying the neural basis of cognitive processes by the anatomical-correlative method [1]. While studying the effect of a brain lesion in his famous patient “Monsieur Tan”, who had a neurosyphilic lesion to the left hemisphere that impaired his language production, Broca concluded that it was possible to infer a causal relationship between a specific brain region and a cognitive function [2]. This discovery ultimately sparked the emergence of neuropsychology, which aims to better understand the link between brain and behavior, and led to a wide interest in the study of patients with various brain lesions. Subsequently, remarkable progress was made using this approach, for example during World War II, where researchers were able to study the effects of focal brain lesions induced by weapons in conjunction with cognitive testing [3].

Despite the numerous and significant insights derived from the “lesion method”, researchers were -and still are- confronted with methodological limitations when trying to ascertain brain-behavior relationships in patient populations. Firstly, lesions are usually large and often encompass multiple brain areas or networks, as they are most frequently acquired through stroke, ischemia, or traumatic brain injury. Secondly, and consequently, multiple functions are often altered simultaneously, inducing substantial variability in the nature and amplitude of the deficits observed in patients with relatively similar and overlapping lesions. Thirdly, patients often suffer from other medical conditions, either preexistent or consequent to injury, further contributing to the heterogeneity of the studied population. Lastly, it is difficult to conduct a study with a large sample of patients with overlapping lesions, which has led to numerous case studies and findings that have been difficult to replicate [4].

The development of non-invasive neuromodulation methods in the early 1980's offered the promise to circumvent many of the methodological caveats associated with the “lesion method”, allowing causal inference in the study of brain-behavior relationship in healthy populations. While repetitive transcranial magnetic stimulation (rTMS) was increasingly used in the mid 1990's to study the influence of so-called “virtual lesions” in different regions of the brain, interest in transcranial direct current stimulation (tDCS) emerged more recently. tDCS involves the induction of a constant low-amperage electric current (usually 1-2 mA) applied to the cortex via surface electrodes positioned on the scalp of the subject that can be used to probe and modulate cortical plasticity in the human cortex [5]. In standard protocols, the “active” electrode is positioned over the region of interest while the “reference” electrode is placed contralaterally over the homologous region or supraorbital area. The current flows from the positively charged anode towards the negatively charged cathode. The effect of tDCS on a specific region is partly determined by the polarity of the stimulation: cortical excitability is thought to be enhanced under the anode, and decreased under the cathode [6].

As with TMS protocols, initial studies using tDCS [6,7] investigated its effects on motor cortex, mainly because of the possibility to directly measure the increase or reduction of cortical excitability through TMS-induced motor evoked potentials (MEPs). Since tDCS was shown to be efficient in this regard, many studies began to report the impact of tDCS on other brain functions in healthy subjects, such as vision [8], language [9], and learning [10].

The investigation of the method's potential for the treatment of different neurological and psychiatric disorders, such as depression [11], stroke [12], and schizophrenia [13] has also recently arisen. In fact, over the past 16 years, over one thousand papers have been published on the use of tDCS on different brain functions. However, studies investigating the effect of tDCS on cognition have shown a lack of specificity and a relative inconsistency in both the modulatory effects and the choice of tDCS parameters, which has led to a large number of heterogenous results. For example, modulation of the dorsolateral prefrontal cortex (DLPFC), which is often chosen as target for tDCS because of its role in numerous high-order cognitive processes, has been associated with both an increase and a decrease in executive functions [14-16] and has been suggested to influence -among others- spatial memory [17], verbal fluency [18], risk taking [19] and craving [20].

Therefore, it remains to be determined to which extent tDCS can compensate for obvious limitations to the lesion method. For example, it is debatable whether tDCS can target specific behaviors associated with a given area when the physiologic impact of tDCS itself can vary considerably between subjects. Indeed, the effect of tDCS on a specific brain area will depend on a variety of factors including electrode montage and size, but also according to size and shape of the participant head and fat tissue amount, among others. As a result, the amount of current induced in a given brain area may vary considerably across individuals. Furthermore, the brain region and neuronal populations that underlie a specific cognitive function may also be subject to important variations. Finally, the effects of tDCS for a given brain region are state-dependent and the state of brain activity will differ for different cognitive functions (even if the same brain area is engaged in different functions).

Another, often overlooked issue arises from the fact that stimulation of a given area produces widespread modulation of brain activity, which in turn can affect multiple cognitive functions simultaneously. This can lead to an important problem of interpretation since the observed effect of stimulation could be due to the interaction of several parallel cognitive effects, which are sometimes in opposite directions. To better understand the challenges of interpretation of results of studies using tDCS to modulate dorsolateral prefrontal cortical functions, we undertook a systematic review of the literature. Care was taken to select and compare studies that target the same area and use similar electrode montages. The international 10-20 electrode system areas F3 and F4 were chosen, as they are the most commonly used in tDCS studies of the DLPFC.

Material and methods

A systematic review of the literature was performed using the following database: PubMed (2000 to jan 2014) and Medline (2000 to jan 2014). We used the following search keywords: “tDCS”, “transcranial direct current stimulation”, “prefrontal”, “DLPFC”, “cognition”. We initially identified 202 articles corresponding to our search criteria. After carefully reviewing the abstract of the different papers, we identified 67 articles investigating only healthy subjects. Of these 67 publications, we selected the 63 articles using F3 and/or F4 as stimulation targets. Subsequently, we read through the full texts of the final sample of articles in order to gather the following information: location of stimulation; electrode montage; duration of stimulation; timing of stimulation and task; intensity; electrode size;

cognitive domain; and results. We also looked through the references of the selected papers for additional relevant papers, which led to the inclusion of one additional paper. Studies were only included if they were published in English and described thoroughly their methodology. Studies that did not directly assess the impact of prefrontal tDCS on a cognitive task were also excluded, leading to the exclusion of two additional studies and a final sample of 61 publications.

An important issue that needs to be taken into consideration when comparing tDCS studies is the electrode montage and the use of terms such as ‘cathodal stimulation’ and ‘anodal stimulation’. It is not possible to apply anodal or cathodal stimulation, as a second electrode is always needed to deliver current to the brain. It is therefore important to emphasize that the ‘site of stimulation’ is not simply the location of one electrode, but rather the combination of the anode and cathode. In the present review, a distinction was made between stimulation paradigms that place one electrode (cathode or anode) over the specific target area (F3 or F4) and the other over a ‘reference’ site (usually the supraorbital area) and those that place both electrodes over the target area bilaterally.

Results

Using the same site of stimulation (F3 and F4, or F3/F4 and reference site), results from the 61 publications suggest that tDCS applied over the prefrontal cortex can influence the performance of a wide range of cognitive functions. The results and description of the studies are shown in Table 1. Note that these results are restricted to the effects of DLPFC stimulation on cognitive tasks, even if a study investigated other regions or if other methods were used to quantify the effects of tDCS (i.e. EEG). In order to be succinct, only the main results of the different studies are reported. Non-significant results in supplementary tasks included in the paradigms are not reported. For a clearer understanding of the effects of different types of stimulation (target regions and polarity) on cognitive function, the results are divided into the seven different types of electrode montages that were used in the included articles.

1. **Cathode over left DLPFC, anode over reference site.** Was shown to *decrease*: a) working memory performance [21]; b) executive function performance (mental flexibility: [22]); c) verbal and semantic performance (visual priming effect:[23]; word fluency task:[18]); d) fear memory consolidation [17]; e) verbal memory performance [17,25-28]). Was shown to *increase*: a) working memory performance [29]; b) semantic processing performance [30-31]; c) executive functioning performance (planning: [15]). Was shown to *modulate*: a) decision making [32].
2. **Cathode over right DLPFC, anode over reference site.** Was shown to *decrease*: a) propensity to punish unfair behavior [33], b) executive function performance (impulsivity: [14]); c) attention control [34]. Was shown to *increase*: a) cognitive control during emotion regulation [35]; b) tolerance to heat pain [29]; c) executive functioning performance (planning: [15]).
3. **Anode over left DLPFC, cathode over reference site.** Was shown to *decrease*: a) working memory performance [36]; b) risk taking behaviors [37]; c) negative

emotions perception [38-39]; d) categorization learning [28]); e) executive functioning performance only in a COMT Met-Met group (cognitive flexibility [40]). Was shown to *increase*: a) working memory performance [21,41-49]; b) positive emotion processing [50-52]; c) pain thresholds [53] ; d) performance on verbal tasks (verbal; word retrieval:[54]; word fluency:[18]); e) executive function performance (mental flexibility: [22]; inhibition: [46]; problem solving: [24,55-56]; planning [15]); f) control of negative emotions [39,57]; g) memory performance and learning [25,27,58-60]. Showed *no significant effect* on: a) mood [61].

4. **Anode over right DLPFC, cathode over reference site.** Was shown to *decrease*: a) risk taking [37]; b) propensity to punish unfair behaviors [33]. Was shown to *increase*: a) working memory performance [48]; b) visuo-spatial memory [46]; c) executive functioning performance (inhibition: [46]); d) pain thresholds [29]; e) emotion regulation [35]; f) memory performance [59]. Showed *no significant effect* on: risk taking [62].

5. **Anode over left DLPFC, cathode over right DLPFC.** Was shown to *decrease*: a) working memory performance [63]; b) food consumption but not craving [20]; c) executive function performance (mental flexibility: [16]). Was shown to *increase*: a) aggressive behaviours and anger [65]; b) executive function performance (mental flexibility: [16]) ; c) language comprehension [66]; d) generation of untruthful answer [67]; e) attention and language performance [68]; f) automaticity for learned materials [66]. Was shown to *modulate*: a) responses to lies [69]; b) decision making [70].

6. **Cathode over left DLPFC, anode over right DLPFC.** Was shown to *increase*: a) executive function performance (mental flexibility: [16]); b) response confidence in a gambling task [71]; c) working memory performance [29]; d) generation of untruthful answers [67]; e) language comprehension [66]. Was shown to *decrease*: a) risk-taking behaviors [19, 62]; b) food craving and consumption [20].

7. **Anode over left DLPFC, anode over right DLPFC.** Was shown to *increase*: a) lie responses [72]; b) attention and vigilance [73].

To summarize, tDCS intending to modulate activity of the same target region (DLPFC) can interfere with a wide range of cognitive functions, from relatively simple and low-level attentional processes, to complex, higher-order functions such as decision-making and working memory. The results also show that the effects of tDCS are highly variable and may be dependent upon the task and stimulation parameters, as illustrated in studies probing working memory function. For instance, working memory was shown to be enhanced by cathodal tDCS over the left DLPFC [29], anodal tDCS over the left DLPFC [21,41-49]; and anodal tDCS over the right DLPFC [48];. Working memory performance was also shown to be decreased by cathodal tDCS over the left DLPFC [21], anodal tDCS over the left DLPFC [36]; and tDCS over bilateral DLPFC (left anodal/right cathodal: [63]). In general, the present review shows that 1) studies probing the same cognitive function using similar tDCS protocols can lead to opposite results; 2) a specific tDCS protocol can induce cognitive effects over a wide variety of functions.

Discussion

The present review highlights the fact that tDCS over the prefrontal cortex can modify a wide range of behaviors from various domains. Due to the presence of many important variations in experimental protocols that have a similar aim (for example reducing excitability of the DLPFC to inhibit a specific cognitive function), it is difficult at this point in time to confidently point to a general pattern describing the effects of "prefrontal tDCS". This is further compounded by the fact that the physiological effects of tDCS themselves are highly variable and dependent upon a variety of individual characteristics.

Polarity

The highly variable effects of tDCS on cognition highlight the fact that the idea of a polarity-specific effect of tDCS, as described originally for the primary motor cortex, cannot be easily transposed to non-motor areas [74]. Theoretically, tDCS increases excitability in the area under the anode, thus facilitating performance on a specific task whereas the opposite effect would occur in the area under the cathode, inhibiting behaviour by decreasing cortical excitability. However, the reality of tDCS effects on cognition is much more complex [75]. For example, many studies report a facilitatory effect associated with stimulation of areas under the cathode [75]. It has been suggested that this effect may be due to the reduction of noise in a specific network that enables facilitation of behaviour [75]. Alternatively, it is possible that 'cathodal tDCS' inhibits a specific function, which would consequently enhance a specific behavior (e.g. faster reaction times).

In a recent study by Batsikadze and collaborators [76], 20 minutes of cathodal tDCS over the primary motor cortex (reference electrode over supraorbital area) was shown to produce an enhancement of corticospinal excitability instead of the expected inhibition when the intensity of the stimulation was doubled from 1 mA to 2 mA. This suggests that different stimulation parameters can directly affect the direction of tDCS-induced changes in cortical excitability. In the studies that were included in the present review, the intensity of stimulation ranged from 260 uA to 2 mA, stimulation duration varied from 3 min to 30 min and electrode size ranged from 8 mm diameter to 100 cm^2. This inconsistency in the choice of the parameters may contribute to the variable direction of the cognitive changes induced by prefrontal tDCS.

State-dependency

Out of the 61 articles presented in this review, 38 used a so-called "online" paradigm where the prefrontal cortex is modulated by tDCS during a specific task. Conversely, 23 studies applied tDCS before a specific task ("offline" paradigm). Both methods are thought to rely on partially distinct mechanisms, which could contribute to the apparent discrepancies among results [77]. Indeed, "offline" stimulation has been suggested to rely on modification of neuronal activity that lasts beyond the period of stimulation, whereas "online" stimulation is believed to modulate a specific network that is involved in the task [77].

Unlike TMS, tDCS does not induce a direct depolarization of neurons but rather is thought to modulate the membrane permeability of neurons leading to a change in the neuronal

firing rate [78]. Therefore, theoretically, tDCS should induce a depolarization of the neurons that are the closest to firing, but that would not have necessarily fired otherwise. In an "online" paradigm, the targeted neuronal populations are already prone to discharge, given that they are presumably part of a neural network thought to be involved in the cognitive task under study [79]. Hence, the effects of prefrontal tDCS are highly dependent on the state of the underlying targeted network, a principle known as "state-dependency" [77,80,81]. In other words, any tDCS-induced activity occurs in the context of a baseline neural activity or a specific state [82]. This state-dependent effect of neuromodulation on the motor region has been taken into consideration from the very first motor studies because the level of cortical excitability is measured before and after the stimulation via MEPs. However, this is more challenging to achieve when studying cognitive functions because many factors can influence the initial state of a neuronal network, such as the level of fatigue, knowledge of the task, pre-existent network connectivity, etc. [81]. For example, a recent meta-analysis showed that "cathodal tDCS" has a very minor effect on language function, which could be explained by the strongly connected brain networks [75]. In other words, because of the high intensity of the firing rate of these strongly interconnected neurons, the current induced by tDCS might not be strong enough to significantly modulate network activity and induce behavioral changes. A further example can be drawn from a tDCS study on motor cortex where the induction of motor imagery during the application of stimulation abolished the excitatory effect of anodal tDCS [83]. In this case, the neurons are already depolarized, which constrains the excitatory effects of the stimulation, possibly by engaging metaplasticity mechanisms.

If the effect of tDCS is dependent on the state of the networks, it must thus also be dependent on the specific task the subjects are engaged in. As a result, the targeted cognitive function has a higher probability of being modulated, and online and offline tDCS protocol would be expected to lead to different results. Similarly, the instructions given to study participants prior to the tDCS would be predicted to exert significant effects onto the results, and thus need to be scripted and controlled with care. Further investigation and leveraging of the "state-dependent" effect could benefit tDCS prefrontal studies in order to better specify the effects of stimulation of a targeted network or function. To date, very few studies have taken this important factor into consideration: within the articles included in the present review, only five mentioned the impact of state-dependency.

Inter-subject variations

Two recent large-scale prospective studies evaluated the inter-subject variation of tDCS effects on primary motor cortex excitability and showed high variability in the participants' response to stimulation [5,84]. Results from Lopez-Alonso and colleagues [5] showed that only 45% of participants respond to "anodal tDCS" over the target area. Similarly, Wiethoff and colleagues [84] showed a response ratio of 45:15 (facilitation: inhibition) after anodal stimulation of the target area and a ratio of 60:40 (facilitation: inhibition) after cathodal stimulation of the target area. As mentioned previously, there exists a large number of *stimulation* parameters that can modulate the physiologic response to tDCS. Chief among them are electrode size, stimulation duration and stimulation intensity. As can be seen from Table 1, these parameters vary widely between studies and considerably limit the

generalizability and comparison of results between studies. Similarly, *participant* characteristics are also important factors that contribute to the variability observed in tDCS studies of prefrontal cortex. Participant head size and shape, as well as amount of fat tissue and fiber orientation all contribute to the physiologic effects of tDCS. When taken together, the presence of these confounding factors strongly suggest that the level of induced current in a specific brain area can vary quite extensively. It is therefore not surprising that the behavioral response to prefrontal tDCS is also subject to large hetererogeneity. All of these factors are compounded by the fact that sample sizes are often relatively small in tDCS studies of prefrontal cortex. A study of cathodal and anodal effects on motor cortex excitability suggested that based on acquired data in healthy individuals, a minimum of 87 participants per group would be needed to achieve a sufficient level of power and confidence to detect a significant difference between patients and healthy subjects [84]. Although this seems to be an extreme case, it should be noted that the mean sample size for the studies included in the present review was only 21 participants.

Conclusion

When using tDCS over the DLPFC with a specific set of parameters, it is possible to modulate a specific cognitive function. However, as highlighted in this review, a given stimulation protocol may simultaneously modulate various other cognitive functions in similar or opposite directions (i.e. facilitation or inhibition). This implies that any effect of prefrontal tDCS on a given task is probably associated with the extensive modulation of a wide range of *multiple* cognitive functions. This, in turn, makes it hard to attribute an observed effect on a specific task to a single mechanism, at least with traditional stimulation protocols. When differing participant characteristics, stimulation parameters and state-dependency effects are also taken into consideration, it becomes clear that more neurobiologic insights of the effects of tDCS are needed to properly interpret the results of studies and appropriately conclude brain-behavior relations. In conclusion, refined protocols that take into account the numerous caveats associated with tDCS and a better standardization of stimulation protocols are needed to improve study quality. One possible way to reduce uncertainty is to monitor the brain impact of tDCS separately and independently of behavioral and cognitive effects. Techniques such as EEG (e.g. [85]), TMS-EEG (e.g. [86]), magnetic resonance spectroscopy (e.g. [87]), functional magnetic resonance imaging (e.g. [88]) and modeling of induced currents (e.g. [89)] have all been shown to be effective in characterizing the physiologic effects of tDCS. Relating behavioral and cognitive effects to the measured brain impact (induced current, physiologic effect) would offer a significant advance for the interpretation of tDCS data.

Acknowledgments

This study was supported by grants from the Canadian Institutes of Health Research, the Natural Sciences and Engineering Research Council of Canada and the Fonds de Recherche du Québec – Santé. ST is supported by a Vanier Canada Graduate Scholarship from the Canadian Institutes of Health Research. JFL is supported by a postdoctoral fellowship from the Canadian Institutes of Health Research. APL is supported in part by grants from the Sidney R. Baer Jr. Foundation, the National Institutes of Health (R01HD069776, R01NS073601, R21 MH099196, R21 NS082870, R21 NS085491, R21 HD07616), Harvard Catalyst | The Harvard Clinical and Translational Science Center (NCRR and the NCATS NIH, UL1 RR025758), and an investigator-initiated grant from Neuronix Ltd. The content is solely the responsibility of the authors and does not necessarily represent the

official views of Harvard Catalyst, Harvard University and its affiliated academic health care centers, the National Institutes of Health or the Sidney R. Baer Jr. Foundation.

References

1. Cubelli R, De Bastiani P. 150 years after Leborgne: why is Paul Broca so important in the history of neuropsychology? Cortex. 2011; 47:146–7. [PubMed: 21112584]
2. Broca P. Sur le siège de la faculté du langage articulé. Bulletins De La Societe d'Anthropologie De Paris. 1865; 6:377–93.
3. Newcombe, F. Missile wounds of the brain: A study of psychological deficits. Oxford University Press; 1969.
4. Koenigs, M.; Tranel, D.; Damasio, AR. The lesion method in cognitive neuroscience Handbook of Psychophysiology. Cambridge University Press; 2007.
5. López-Alonso V, Cheeran B, Río-Rodríguez D, Fernández-del-Olmo M. Brain Stimul. 2014; 7:372–80. [PubMed: 24630849]
6. Nitsche MA, Paulus W. Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. J Physiol. 2000; 527:633–9. [PubMed: 10990547]
7. Priori A, Berardelli A, Rona S, Accornero N, Manfredi M. Polarization of the human motor cortex through the scalp. Neuroreport. 1998; 9:2257–60. [PubMed: 9694210]
8. Antal A, Kincses TZ, Nitsche MA, Paulus W. Modulation of moving phosphene thresholds by transcranial direct current stimulation of V1 in human. Neuropsychologia. 2003; 41:1802–7. [PubMed: 14527543]
9. Floel A, Rösser N, Michka O, Knecht S, Breitenstein C. Noninvasive brain stimulation improves language learning. J Cogn Neurosci. 2008; 20:1415–22. [PubMed: 18303984]
10. Kincses TZ, Antal A, Nitsche MA, Bártfai O, Paulus W. Facilitation of probabilistic classification learning by transcranial direct current stimulation of the prefrontal cortex in the human. Neuropsychologia. 2004; 42:113–7. [PubMed: 14615081]
11. Nitsche MA. Transcranial direct current stimulation: a new treatment for depression? Bipolar Disorders. 2002; 4(Suppl 1):98–9. [PubMed: 12479691]
12. Fregni F, Boggio PS, Mansur CG, Wagner T, Ferreira MJL, Lima MC, et al. Transcranial direct current stimulation of the unaffected hemisphere in stroke patients. Neuroreport. 2005; 16:1551–5. [PubMed: 16148743]
13. Tranulis C, Sepehry AA, Galinowski A, Stip E. Should we treat auditory hallucinations with repetitive transcranial magnetic stimulation? A metaanalysis Can J Psychiatry. 2008; 53:577–86.
14. Beeli G, Casutt G, Baumgartner T, Jäncke L. Modulating presence and impulsiveness by external stimulation of the brain. Behav Brain Funct. 2008; 4:33. [PubMed: 18680573]
15. Dockery CA, Hueckel-Weng R, Birbaumer N, Plewnia C. Enhancement of Planning Ability by Transcranial Direct Current Stimulation. J Neurosci. 2009; 29:7271–7. [PubMed: 19494149]
16. Leite J, Carvalho S, Fregni F, Boggio PS, Gonçalves OF. Transcranial direct current stimulation (tDCS) of the left dorsolateral prefrontal cortex modulates declarative memory. Brain Stimul. 2012; 5:231–4. [PubMed: 21840287]
17. Asthana M, Nueckel K, Mühlberger A, Neueder D, Polak T, Domschke K, et al. Effects of transcranial direct current stimulation on consolidation of fear memory. Front Psychiatry. 2013; 4:1–7. [PubMed: 23346060]
18. Vannorsdall TD, Schretlen DJ, Andrejczuk M, Ledoux K, Bosley LV, Weaver JR, et al. Altering automatic verbal processes with transcranial direct current stimulation. Front Psychiatry. 2012; 3:73. [PubMed: 22888321]
19. Fecteau S, Knoch D, Fregni F, Sultani N, Boggio P, Pascual-Leone A. Diminishing Risk-Taking Behavior by Modulating Activity in the Prefrontal Cortex: A Direct Current Stimulation Study. J Neurosci. 2007; 27:12500–5. [PubMed: 18003828]
20. Fregni F, Orsati F, Pedrosa W, Fecteau S, Tome FAM, Nitsche MA, et al. Transcranial direct current stimulation of the prefrontal cortex modulates the desire for specific foods. Appetite. 2008; 51:34–41. [PubMed: 18243412]

21. Zaehle T, Sandmann P, Thorne JD, Jäncke L, Herrmann CS. Transcranial direct current stimulation of the prefrontal cortex modulates working memory performance: combined behavioural and electrophysiological evidence. BMC Neurosci. 2011; 12:2. [PubMed: 21211016]
22. Leite J, Carvalho S, Fregni F, Gonçalves OF. Task-Specific Effects of tDCS-Induced Cortical Excitability Changes on Cognitive and Motor Sequence Set Shifting Performance. PLoS ONE. 2011; 6:e24140. [PubMed: 21909415]
23. Kongthong N, Minami T, Nakauchi S. Semantic processing in subliminal face stimuli: an EEG and tDCS study. Neurosci Lett. 2013; 544:141–6. [PubMed: 23587808]
24. Elmer S, Burkard M, Renz B, Meyer M, Jäncke L. Direct current induced short-term modulation of the left dorsolateral prefrontal cortex while learning auditory presented nouns. Behav Brain Funct. 2009; 5:29. [PubMed: 19604352]
25. Javadi AH, Cheng P, Walsh V. Short duration transcranial direct current stimulation (tDCS) modulates verbal memory. Brain Stimul. 2012; 5:468–74. [PubMed: 21962975]
26. Hammer A, Mohammadi B, Schmicker M, Saliger S, Münte TF. Errorless and errorful learning modulated by transcranial direct current stimulation. BMC Neurosci. 2011; 12:72. [PubMed: 21781298]
27. Javadi AH, Cheng P. Transcranial direct current stimulation (tDCS) enhances reconsolidation of long-term memory. Brain Stimul. 2013; 6:668–74. [PubMed: 23137702]
28. Ambrus GZG, Zimmer M, Kincses ZT, Harza I, Kovács G, Paulus W, et al. Neuropsychologia. 2011; 49:1974–80. [PubMed: 21440562]
29. Mylius V, Jung M, Menzler K, Haag A, Khader PH, Oertel WH, et al. Effects of transcranial direct current stimulation on pain perception and working memory. Ejp. 2012; 16:974–82. [PubMed: 22337597]
30. Balconi M, Vitaloni S. Dorsolateral pFC and the Representation of the Incorrect Use of an Object: The Transcranial Direct Current Stimulation Effect on N400 for Visual and Linguistic Stimuli. J Cogn Neurosci. 2014; 26:305–18. [PubMed: 24144247]
31. Balconi M, Vitaloni S. The tDCS effect on alpha brain oscillation of correct vs. incorrect object use: The contribution of the left DLPFC. Neurosci Lett. 2012; 517:25–9. [PubMed: 22516461]
32. Mengarelli F, Spoglianti S, Avenanti A, di Pellegrino G. Cathodal tDCS Over the Left Prefrontal Cortex Diminishes Choice-Induced Preference Change. Cereb Cortex. 2013
33. Knoch D, Nitsche MA, Fischbacher U, Eisenegger C, Pascual-Leone A, Fehr E. Studying the Neurobiology of Social Interaction with Transcranial Direct Current Stimulation-The Example of Punishing Unfairness. Cereb Cortex. 2008; 18:1987–90. [PubMed: 18158325]
34. Tanoue RT, Jones KT, Peterson DJ, Berryhill ME. Differential frontal incolvement in shifts of internal and perceptual attention. Brain Stimul. 2013; 6:675–82. [PubMed: 23266133]
35. Feeser M, Prehn K, Kazzer P, Mungee A, Bajbouj M. Transcranial Direct Current Stimulation Enhances Cognitive Control During Emotion Regulation. Brain Stimul. 2013
36. Fregni F, Boggio PS, Nitsche M, Bermpohl F, Antal A, Feredoes E, et al. Anodal transcranial direct current stimulation of prefrontal cortex enhances working memory. Exp Brain Res. 2005; 166:23–30. [PubMed: 15999258]
37. Beeli G, Koeneke S, Gasser K, Jäncke L. Brain stimulation modulates driving behavior. Behav Brain Funct. 2008; 4:34. [PubMed: 18684333]
38. Boggio PS, Zaghi S, Fregni F. Modulation of emotions associated with images of human pain using anodal transcranial direct current stimulation (tDCS). Neuropsychologia. 2009; 47:212–7. [PubMed: 18725237]
39. Maeoka H, Matsuo A, Hiyamizu M, Morioka S, Ando H. Influence of transcranial direct current stimulation of the dorsolateral prefrontal cortex on pain related emotions: a study using electroencephalographic power spectrum analysis. Neurosci Lett. 2012; 512:12–6. [PubMed: 22326385]
40. Plewnia C, Zwissler B, Längst I, Maurer B, Giel K, Krüger R. Effects of transcranial direct current stimulation (tDCS) on executive functions: influence of COMT Val/Met polymorphism. Cortex. 2013; 49:1801–7. [PubMed: 23237479]

41. Ohn SH, Park CI, Yoo WK, Ko MH, Choi KP, Kim GM, et al. Time-dependent effect of transcranial direct current stimulation on the enhancement of working memory. Neuroreport. 2008; 19:43–7. [PubMed: 18281890]
42. Mulquiney PG, Hoy KE, Daskalakis ZJ, Fitzgerald PB. Improving working memory: exploring the effect of transcranial random noise stimulation and transcranial direct current stimulation on the dorsolateral prefrontal cortex. Clin Neurophysiol. 2011; 122:2384–9. [PubMed: 21665534]
43. Teo F, Hoy KE, Daskalakis ZJ, Fitzgerald PB. Investigating the Role of Current Strength in tDCS Modulation of Working Memory Performance in Healthy Controls. Front Psychiatry. 2011; 2:45. [PubMed: 21811474]
44. Andrews SC, Hoy KE, Enticott PG, Daskalakis ZJ, Fitzgerald PB. Improving working memory: the effect of combining cognitive activity and anodal transcranial direct current stimulation to the left dorsolateral prefrontal cortex. Brain Stimul. 2011; 4:84–9. [PubMed: 21511208]
45. Gladwin TE, den Uyl TE, Wiers RW. Anodal tDCS of dorsolateral prefrontal cortex during an implicit association test. Neurosci Lett. 2012; 517:82–6. [PubMed: 22531748]
46. Jeon SY, Han SJ. Improvement of the Working Memory and Naming by Transcranial Direct Current Stimulation. Ann Rehabil Med. 2012; 36:585. [PubMed: 23185722]
47. Hoy KE, Emonson MRL, Arnold SL, Thomson RH, Daskalakis ZJ, Fitzgerald PB. Testing the limits: Investigating the effect of tDCS dose on working memory enhancement in healthy controls. Neuropsychologia. 2013; 51:1777–84. [PubMed: 23751169]
48. Meiron O, Lavidor M. Unilateral prefrontal direct current stimulation effects are modulated by working memory load and gender. Brain Stimul. 2013; 6:440–7. [PubMed: 22743075]
49. Vanderhasselt MA, De Raedt R, Brunoni AR, Campanhã C, Baeken C, Remue J, et al. tDCS over the left prefrontal cortex enhances cognitive control for positive affective stimuli. PLoS ONE. 2013; 8:e62219. [PubMed: 23704874]
50. Nitsche MA, Koschack J, Pohlers H, Hullemann S, Paulus W, Happe S. Effects of frontal transcranial direct current stimulation on emotional state and processing in healthy humans. Front Psychiatry. 2012; 3:58, 1–10. [PubMed: 22723786]
51. Cattaneo Z, Lega C, Flexas A, Nadal M, Munar E, Cela-Conde CJ. The world can look better: enhancing beauty experience with brain stimulation. SCAN. 2013:1–10.
52. Vanderhasselt MA, De Raedt R, Brunoni AR, Campanhã C, Baeken C, Remue J, et al. tDCS over the Left Prefrontal Cortex Enhances Cognitive Control for Positive Affective Stimuli. PLoS ONE. 2013; 8:e62219. [PubMed: 23704874]
53. Boggio PS, Zaghi S, Lopes M, Fregni F. Modulatory effects of anodal transcranial direct current stimulation on perception and pain thresholds in healthy volunteers. Eur J Neurol. 2008; 15:1124–30. [PubMed: 18717717]
54. Fertonani A, Rosini S, Cotelli M, Rossini PM, Miniussi C. Naming facilitation induced by transcranial direct current stimulation. Behav Brain Res. 2010; 208:311–8. [PubMed: 19883697]
55. Metuki N, Sela T, Lavidor M. Enhancing cognitive control components of insight problems solving by anodal tDCS of the left dorsolateral prefrontal cortex. Brain Stimul. 2012; 5:110–5. [PubMed: 22483547]
56. Cerruti C, Schlaug G. Anodal transcranial direct current stimulation of the prefrontal cortex enhances complex verbal associative thought. J Cogn Neurosci. 2009; 21:1980–7. [PubMed: 18855556]
57. Peña-Gómez C, Vidal-Piñeiro D, Clemente IC, Pascual-Leone A, Bartrés-Faz D. Down-Regulation of Negative Emotional Processing by Transcranial Direct Current Stimulation: Effects of Personality Characteristics. PLoS ONE. 2011; 6:e22812. [PubMed: 21829522]
58. Javadi AH, Walsh V. Transcranial direct current stimulation (tDCS) of the left dorsolateral prefrontal cortex modulates declarative memory. Brain Stimul. 2012; 5:231–41. [PubMed: 21840287]
59. Manenti R, Brambilla M, Petesi M, Ferrari C, Cotelli M. Enhancing verbal episodic memory in older and young subjects after non-invasive brain stimulation. Front Aging Neurosci. 2013; 5:49. [PubMed: 24062685]

60. Foerster A, Rocha S, Wiesiolek C, Chagas AP, Machado G, Silva E, et al. Site-specific effects of mental practice combined with transcranial direct current stimulation on motor learning. Eur J Neurosci. 2013; 37:786–94. [PubMed: 23279569]
61. Motohashi N, Yamaguchi M, Fujii T, Kitahara Y. Mood and cognitive function following repeated transcranial direct current stimulation in healthy volunteers: A preliminary report. Neurosci Res. 2013; 77:64–9. [PubMed: 23811267]
62. Fecteau S, Pascual-Leone A, Zald DH, Liguori P, Théoret H, Boggio PS, et al. Activation of Prefrontal Cortex by Transcranial Direct Current Stimulation Reduces Appetite for Risk during Ambiguous Decision Making. J Neurosci. 2007; 27:6212–8. [PubMed: 17553993]
63. Marshall L, Mölle M, Siebner HR, Born J. Bifrontal transcranial direct current stimulation slows reaction time in a working memory task. BMC Neurosci. 2005; 6:23. [PubMed: 15819988]
64. Iuculano T, Cohen Kadosh R. The Mental Cost of Cognitive Enhancement. J Neurosci. 2013; 33:4482–6. [PubMed: 23467363]
65. Hortensius R, Schutter DJLG, Harmon-Jones E. When anger leads to aggression: induction of relative left frontal cortical activity with transcranial direct current stimulation increases the anger-aggression relationship. SCAN. 2012; 7:342–7. [PubMed: 21421731]
66. Sela T, Ivry RB, Lavidor M. Prefrontal control during semantic decision task that invoves idiom comprehension: a transcranial direct current stimulation study. Neuropsychologia. 2012; 50:2271–80. [PubMed: 22687558]
67. Fecteau S, Boggio P, Fregni F, Pascual-Leone A. Modulation of untruthful responses with non-invasive brain stimulation. Front Psychiatry. 2013; 3:1–9.
68. Nozari N, Thompson-Schill SL. More attention when speaking: Does it help or does it hurt? Neuropsychologia. 2013; 51:2770–80. [PubMed: 24012690]
69. Mameli F, Mrakic-Sposta S, Vergari M, Fumagalli M, Macis M, Ferrucci R, et al. Dorsolateral prefrontal cortex specifically processes general - but not personal - knowledge deception: multiple brain networks for lying. Behav Brain Res. 2010; 211:164–8. [PubMed: 20307584]
70. Hecht D, Walsh V, Lavidor M. Transcranial Direct Current Stimulation Facilitates Decision Making in a Probabilistic Guessing Task. J Neurosci. 2010; 30:4241–5. [PubMed: 20335459]
71. Minati L, Campanhã C, Critchley HD, Boggio PS. Effects of transcranial direct-current stimulation (tDCS) of the dorsolateral prefrontal cortex (DLPFC) during a mixed-gambling risky decision-making task. Cogn Neurosci. 2012; 3:80–8. [PubMed: 24168688]
72. Priori A, Mameli F, Cogiamanian F, Marceglia S, Tiriticco M, Mrakic-Sposta S, et al. Lie-Specific Involvement of Dorsolateral Prefrontal Cortex in Deception. Cereb Cortex. 2008; 18:451–5. [PubMed: 17584853]
73. Nelson JT, McKinley RA, Golob EJ, Warm JS, Parasuraman R. Enhancing vigilance in operators with prefrontal cortex transcranial direct current stimulation (tDCS). Neuroimage. 2014; 85:909–17. [PubMed: 23235272]
74. Nitsche MA, Cohen LG, Wassermann EM, Priori A, Lang N, Antal A, et al. Transcranial direct current stimulation: State of the art 2008. Brain Stimul. 2008; 1:206–23. [PubMed: 20633386]
75. Jacobson L, Koslowsky M, Lavidor M. tDCS polarity effects in motor and cognitive domains: a meta-analytical review. Exp Brain Res. 2011; 216:1–10. [PubMed: 21989847]
76. Batsikadze G, Moliadze V, Paulus W, Kuo MF, Nitsche MA. Partially non-linear stimulation intensity-dependent effects of direct current stimulation on motor cortex excitability in humans. J Physiol. 2013; 59:1987–2000. [PubMed: 23339180]
77. Miniussi C, Harris JA, Ruzzoli M. Modelling non-invasive brain stimulation in cognitive neuroscience. Neurosci Biobehav Rev. 2013; 37:1702–12. [PubMed: 23827785]
78. Liebetanz D, Nitsche MA, Tergau F, Paulus W. Pharmacological approach to the mechanisms of transcranial DC-stimulation-induced after-effects of human motor cortex excitability. Brain. 2002; 125:2238–47. [PubMed: 12244081]
79. Miniussi, C.; Ruzzoli, M. Transcranial stimulation and cognition. 1st. Elsevier B.V; 2013.
80. Weigand A, Richtermeier A, Feeser M, Guo JS, Briesemeister BB, Grimm S, et al. State-dependent effects of prefrontal repetitive transcranial magnetic stimulation on emotional working memory. Brain Stimul. 2013; 6:905–12. [PubMed: 23928102]

81. Silvanto J, Muggleton N, Walsh V. State-dependency in brain stimulation studies of perception and cognition. Trends Cogn Sci. 2008; 12:447–54. [PubMed: 18951833]
82. Silvanto J, Pascual-Leone A. State-dependency of transcranial magnetic stimulation. Brain Topogr. 2008; 21:1–10. [PubMed: 18791818]
83. Quartarone A, Morgante F, Bagnato S, Rizzo V, Sant'Angelo A, Aiello E, et al. Long lasting effects of transcranial direct current stimulation on motor imagery. Neuroreport. 2004; 15:1287–91. [PubMed: 15167551]
84. Wiethoff S, Hamada M, Rothwell JC. Variability in response to transcranial direct current stimulation of the motor cortex. Brain Stimul. 2014; 7:468–75. [PubMed: 24630848]
85. Keeser D, Padberg F, Reisinger E, Pogarell O, Kirsch V, Palm U, Karch S, Möller HJ, Nitsche MA, Mulert C. Prefrontal direct current stimulation modulates resting EEG and event-related potentials in healthy subjects: a standardized low resolution tomography (sLORETA) study. Neuroimage. 2011; 55:644–657. [PubMed: 21146614]
86. Romero Lauro LJ, Rosanova M, Mattavelli G, Convento S, Pisoni A, Opitz A, Bolognini N, Vallar G. TDCS increases cortical excitability: Direct evidence from TMS-EEG. Cortex. 2014; 58C:99–111. [PubMed: 24998337]
87. Stagg CJ, Best JG, Stephenson MC, O'Shea J, Wylezinska M, Kincses ZT, Morris PG, Matthews PM, Johansen-Berg H. Polarity-sensitive modulation of cortical neurotransmitters by transcranial stimulation. J Neurosci. 2009; 29:5202–5206. [PubMed: 19386916]
88. Weber MJ, Messing SB, Rao H, Detre JA, Thompson-Schill SL. Prefrontal transcranial direct current stimulation alters activation and connectivity in cortical and subcortical reward systems: A tDCS-fMRI study. Hum Brain Mapp. 2014; 35:3673–3686. [PubMed: 24453107]
89. Truong DQ, Magerowski G, Blackburn GL, Bikson M, Alonso-Alonso M. Computational modeling of transcranial direct current stimulation (tDCS) in obesity: Impact of head fat and dose guidelines. Neuroimage Clin. 2013; 2:759–766. [PubMed: 24159560]

Table 1

Authors	Target Region(s)	Montage	Timing of tDCS	Duration	Intensity	Electrode Size	Cognitive Domain	Cognitive effect
[36] Fregni *et al*. (2005)	Left DLPFC	Anodal F3 / Cathodal contra SO Cathodal F3 / Anodal contra SO Sham (F3 /SO)	Online	10 min	1 mA	35 cm^2	Working memory	**1** Left anodal: increased performance (sequential letter task)
[63] Marshall *et al*. (2005)	Left/Right DLPFC	Anodal F3 / Cathodal F4 Reference: mastoidsSham (F3/F4/ mastoid)	Online	15 min (15s on and 15s off, intermittent)	260 uA	Diameter: 8 mm	Working memory	**1** Bilateral (left anodal/right cathodal): decreased performance (slower RTs)
[62] Fecteau *et al*. (2007)	Left/Right DLPFC	Anodal F3 / Cathodal F4 Anodal F4 / Cahodal F3Sham (F3 / F4) Anodal F3 / Cathodal contra SO Anodal F4 / Cahodal contra SO Sham (F3 or F4 / contra. SO)	Online	20 min	2 mA	35 cm^2	Risk taking	**1** Bilateral (left cathodal/right anodal): decreased risk taking (Baloon Analogue Risk Task) **2** Right anodal: no sign. effect on risk taking
[19] Fecteau *et al*. (2007)	Left/Right DLPFC	Anodal F3 / Cathodal F4 Anodal F4 / Cahodal F3 Sham (F3 / F4)	Online	15 min	2 mA	35 cm^2	Risk taking	**1** Bilateral (left cathodal/right anodal): reduced risk taking (Risk Task)
[37] Beeli *et al*. (2008)	Left DLPFCRight DLPFC	Anodal F3 or F4 / Cathodal ipsi. mastoid Cathodal F3 or F4 / Anodal ipsi. mastoid	Offline	15 min	1 mA	35 cm^2	Risk taking	**1** Left anodal: reduced risk taking behaviours (driving stimulator) **2** Right anodal: reduced risk taking behaviours (driving stimulator)
[14] Beeli *et al*. (2008)	Right DLPFC	Anodal FC3 / Cathodal ipsi. mastoid	Online	5.5 min	1.5 mA	35 cm^2	Executive function (impulsivity) Feeling of “presence”	**1** Right cathodal: increases

Authors	Target Region(s)	Montage	Timing of tDCS	Duration	Intensity	Electrode Size	Cognitive Domain	Cognitive effect
		Cathodal FC3 / Anodal ipsi. Mastoid Cathodal FC3 / Anodal ipsi. Mastoid Sham						impulsiveness (Go-Nogo task)
[53] Boggio *et al* (2008)	Left DLPFC	Anodal F3 / Cathodal right SO Sham (F3 / SO)	Online	5 min	2 mA	35 cm^2	Pain perception	**1** Left anodal: decreased pain perception (higher pain threshold)
[20] Fregni *et al.* (2008)	Left/right DLPFC	Anodal F3 / Cathodal F4 Anodal F4 / Cahodal F3 Sham (F3 / F4)	Offline	20 min	2 mA	35 cm^2	Food craving	**1** Bilateral (left anodal/right cathodal): reduced food consumption but not craving **2** Bilateral (left cathodal/right anodal): reduced food craving and consumption
[33] Knoch *et al.* (2008)	Right DLPFC	Cathodal F4 / Anodal contra. SO	Online	14 min	1.5 mA	35 cm^2 Reference: 100 cm^2	Emotions Social behaviours	**1** Right cathodal: reduced propensity to punish unfair behaviour
[41] Ohn *et al.* (2008)	Left DLPFC	Anodal F3 / Cathodal right SO Sham (F3 / SO)	Online	30 min	1 mA	25 cm^2	Verbal working memory	**1** Left anodal: enhanced performance (3-back)
[72] Priori *et al.* (2008)	Left/Right DLPFC	Anodal F3 and F4 / Cathodal deltoid Cathodal F3 and F4 / Anodal deltoid Sham (F3-F4 / Deltoid)	Offline	10 min	1.5 mA	Active:32 cm^2 Reference:64 cm^2	Decision making	**1** Bilateral (left anodal/ right anodal): increased lie responses
[38] Boggio *et al*. (2009)	Left DLPFC	Anodal F3 / Cathodal contra SO Sham (F3 / SO)	Online	5 min	2 mA	35 cm^2	Emotion processing Pain	**1** Left anodal: decreased negative emotions perception (unpleasantness and emotional discomfort)

Authors	Target Region(s)	Montage	Timing of tDCS	Duration	Intensity	Electrode Size	Cognitive Domain	Cognitive effect
[56] Cerruti *et al.*(2009)	Left DLPFCRight DLPFC	Anodal F3 or F4 / Cathodal contra SO Cathodal F3 or F4 / Anodal contra SO Sham F3/F4	Online	20 min	1 mA	16.3 cm^2 on F3/F4 30 cm^2 on SO	Verbal problem solving	**1** Left anodal: improvement (RAT task) **2** Cathodal: no sign. effect
[15] Dockery *et al.* (2009)	Left DLPFC	Anodal F3 / Cathodal contra. SO Cathodal F3 / Anodal contra. SO Sham (F3 / SO)	Online	15 min	1 mA	35 cm^2	Executive functioning (planning)	**1** Left cathodal and left anodal: enhanced performance (Tower of London)
[24] Elmer *et al.*(2009)	Left DLPFCRight DLPFC	Anodal F3 or F4 / Cathodal mastoid Cathodal F3 or F4 / Anodal mastoid Sham (F3 or F4/ Mastoid)	Online	5 min	1.5 mA	28 cm^2 on F3/F4 100 cm^2 on SO	Verbal learning	**1** Left cathodal: impaired short-term verbal learning
[54] Fertonani*et al.* (2010)	Left DLPFC	Anodal F3 / Cathodal shoulder Cathodal F3 / Cathodal shoulder Sham (F3/Shoulder)	Offline	8-10 min	2 mA	35 cm^2	Language (picture naming)	**1** Left anodal: facilitation (faster RTs) **2** Left cathodal: no sign. effect
[70] Hecht *et al.* (2010)	Left/Right DLPFC	Anodal F3 / Cathodal F4 Anodal F4 / Cahodal F3 Control (no stimulation)	Online	22 min	2 mA	9 cm^2	Decision making	**1** Bilateral (left anodal/right cathodal): modified strategies (Probabilistic Guessing Task)
[69] Mameli *et al.* (2010)	Left/RightDLPFC	Anodal F3 / Anodal F4 / Reference right deltoid muscle Sham (F3 / F4 / Deltoid)	Offline	15 min	2 mA	Target: 32 cm^2 Reference: 64 cm^2	Decision making (lies)	**1** Bilateral (left anodal/ right anodal): modulated responses to lies (decreased RTs)
[28] Ambrus *et al.* (2011)	Left DLPFCRight DLPFC	Anodal F3 or F4 / Cathodal Cz Cathodal F4 / Anodal Cz Sham (F4/ Cz)	Online	10 min	1 mA	35 cm^2	Categorization learning	**1** Left anodal and right anodal: decreased performance (accuracy of identification of prototype)

Authors	Target Region(s)	Montage	Timing of tDCS	Duration	Intensity	Electrode Size	Cognitive Domain	Cognitive effect
[44] Andrews *et al.*, (2011)	Left DLPFC	Anodal F3/Cathodal SO	Online	10 min	1 mA	35 cm^2	Working memory	**1** Left anodal: enhanced performance (digit span forward)
[26] Hammer *et al.* (2011)	Left DLPFC	Anodal F3 / Cathodal contra. SO Cathodal F3 / Cathodal contra. SO Sham (F3 / SO)	Online	30 min	1 mA	35 cm^2	Memory	**1** Left cathodal: hampered memory performance after errorful learning
[22] Leite *et al.*, (2011)	Left DLPFC	Anodal F3 / Cathodal contra. SO Cathodal F3 / Cathodal contra. SO Sham (F3 / SO)	Online	15min	1 mA	35 cm^2	Executive functions (mental/ motor flexibility)	**1** Left anodal: increased performance (set switching task) **2** Left cathodal: decreased performance (set switching task)
[42] Mulquiney *et al.*, (2011)	Left DLPFC	Anodal F3 / Cathodal contra. SO Sham (F3 / SO)	Online	10 min	1 mA	35 cm^2	Working memory	**1** Left anodal: improved speed of performance (2-back task).
[57] Peña-Gómez *et al.* (2011)	Left DLPFC	Anodal F3 / Cathodal C4 Sham (F3 / C4)	Online	20 min	1 mA	35 cm^2	Emotion processing	**1** Left anodal: enhanced down-regulation of negative emotions
[43] Teo *et al.*, (2011)	Left DLPFC	Anodal F3 / Cathodal right SO Sham (F3 / SO)	Online	20 min	1 mA and2 mA	35 cm^2	Working memory	**1** Left anodal: enhanced performance at 2 mA (faster RTs, no effect on accuracy)
[21] Zaehle *et al.* (2011)	Left DLPFC	Anodal F3 / Ipsi. mastoid Cathodal F3 / Ipsi. mastoid Sham (F3 / mastoid)	Offline	15 min	1 mA	35 cm^2	Working memory	**1** Left anodal: increased performance

Authors	Target Region(s)	Montage	Timing of tDCS	Duration	Intensity	Electrode Size	Cognitive Domain	Cognitive effect
								2 Left cathodal: reduced performance
[31] Balconi *et al.* (2012)	Left DLPFC	Cathodal F3 / Anodal right SO Sham (F3/ Right SO)	Offline	15 min	2 mA	35 cm^2	Semantic congruence processing	**1** Left cathodal: improved performance (reduced RTs for incorrect object)
[45] Gladwin *et al.* (2012)	Left DLPFC	Anodal F3 / Cathodal right SO Sham (F3/Right SO)	Offline	10 min	1 mA	35 cm^2	Working memory	**1** Left anodal: improved performance (congruent blocks of the IAT task)
[65] Hortensius *et al.* (2012)	Left/Right DLPFC	Anodal F3 / Cathodal F4 Anodal F4 / Cahodal F3 Sham (F3 / F4)	Offline	15 min	2 mA	35 cm^2	Emotionregulation	**1** Bilateral (left anodal/right cathodal): increased aggressive behaviours and anger
[58] Javadi *et al.* (2012)	Left DLPFC	Anodal F3 / Cathodal contra. SO Cathodal F3 / Cathodal contra. SO Sham (F3 / SO)	Online	20 min	1 mA	Target: 12.2 cm^2 Reference:30.2 cm^2	Declarative memory	**1** Left anodal: enhanced memory performance (applied during encoding and recognition (trend)) **2** Left cathodal: impaired memory performance (applied during encoding and recognition)
[25] Javadi *et al.* (2012)	Left DLPFC	Anodal F3 / Cathodal contra. SO Cathodal F3 / Cathodal contra. SO Sham (no stimulation)	Online	3 min	1.5 mA	Target: 12.2 cm^2 Reference:30.2 cm^2	Verbal memory	**1** Left anodal: enhanced memory performance (accuracy)1) Left cathodal: impaired memory

Brain Stimul. Author manuscript; available in PMC 2015 November 01.

Authors	Target Region(s)	Montage	Timing of tDCS	Duration	Intensity	Electrode Size	Cognitive Domain	Cognitive effect
								performance (accuracy) performance (accuracy)
[46] Jeon *et al.* (2012)	Left DLPFCRight DLPFC	Anodal F3 / Cathodal right SO Anodal F4 / Cathodal left SO Sham (F3 or F4/ SO)	Offline	20 min	1 mA	35 cm^2	Working memory Attention Executive functions (inhibition, mental flexibility)	**1** Left anodal: enhanced performance (stroop, digit span backwards, K-BNT) **2** Right anodal: enhanced performance (stroop, visuospatial memory/ attention task)
[16] Leite *et al.* (2012)	Left/Right DLPFC	Anodal F3 / Cathodal F4 Anodal F4 / Cahodal F3 Sham (F3 / F4)	Online	<30 min	2 mA	35 cm^2	Executive functions (mental flexibility)	**1** Bilateral (left anodal/right cathodal): increased switching performance (letter-digit task), improved accuracy and decreased switching performance (vowel-consonant parity task) **2** Bilateral (left cathodal): increased accuracy (letter-digit task)
[39] Maeoka *et al.* (2012)	Left DLPFC	Anodal F3 / Cathodal contra. SO Sham (F3 / SO)	Offline	20 min	1 mA	35 cm^2	Emotion processing	**1** Left anodal: decreased negative emotion (decreased unpleasantness subjective report)
[55] Metuki *et al.* (2012)	Left DLPFC	Anodal F3 / Cathodal Fp2 Sham (F3 / Fp2)	Online	11 min	1 mA	35 cm^2	Executive functions: Problem solving	**1** Left anodal: increased performance

Authors	Target Region(s)	Montage	Timing of tDCS	Duration	Intensity	Electrode Size	Cognitive Domain	Cognitive effect
								(verbal insight task) (verbal insight task)
[71] Minati *et al.* (2012)	Left/Right DLPFC	Anodal F3 / Cathodal F4 Anodal F4 / Cahodal F3 Sham (F3 / F4)	Online	20.5 ± 4.1min	2 mA	N.S.	Decision making	**1** Bilateral (left cathodal/right anodal): no sign. effect on risk taking (Gambling Task) but enhanced response confidence
[29] Mylius *et al.* (2012)	Left DLPFC Right DLPFC	Anodal F3 or F4 / Cathodal contra SO Cathodal F3 or F4 / Anodal contra SO Sham (F3 or F4 / contra SO)	Online	20 min	2 mA	35 cm^2	Working memory Pain perception	**1** Right anodal: increased tolerance to pain **2** Left cathodal: decreased number of outliers in 2-back task
[50] Nitsche *et al.* 2012	Left DLPFC	Anodal F3 / Cathodal contra. SO Cathodal F4 / Anodal contra. SO Sham (F3 / contra. SO)	OfflineOnline	10 min or 20 min	1 mA	35 cm^2	Emotion processing	**1** Left anodal: enhanced positive emotion (positive emotion detection)
[66] Sela *et al.*(2012)	Left/Right DLPFC	Anodal F3 / Cathodal F4 Cathodal F3 / Anodal F4 Sham (F3/F4)	Offline	15 min	1.5 mA	35 cm^2	Language comprehension (semantic processing)	**1** Bilateral (left anodal/right cathodal): enhancement of performance (predictable idioms) **2** Bilateral (left cathodal/ right anodal): enhancement of performance (unpredictable idioms)

Brain Stimul. Author manuscript; available in PMC 2015 November 01.

Authors	Target Region(s)	Montage	Timing of tDCS	Duration	Intensity	Electrode Size	Cognitive Domain	Cognitive effect
[18] Vannorsdall*et al.* (2012)	Left DLPFC	Anodal F3 / Cathodal Cz Cathodal F3 / Cathodal Cz Sham (F3 or F4 / Cz)	Online	30 min	1 mA	27 cm^2	Verbal fluency	**1** Left anodal: increased performance (category-cued) **2** Left cathodal: decreased performance (clustered words)
[17] Asthana *et al.* (2013)	Left DLPFC	Anodal F3 / Ipsi. mastoid Cathodal F3 / Ipsi. mastoid Sham (F3 / mastoid)	Offline	12 min	1 mA	35 cm^2	Fear memory	**1** Left cathodal: disrupted fear memory consolidation
[51] Cattaneo *et al.* (2013)	Left DLPFC	Anodal (between F3 and F5) / Cathodal contra. SO Sham (F3-F5 / SO)	Offline	20 min	2 mA	35 cm^2	Emotion processing	**1** Left anodal: enhancement of beauty experience
[67] Fecteau *et al.* (2013)	Left/Right DLPFC	Anodal F3 / Cathodal F4 Anodal F4 / Cahodal F3 Sham (F3 / F4)	Offline	20 min	2 mA	35 cm^2	Decision making	**1** Bilateral (left cathodal/right anodal): enhanced the generation of untruthful answers **2** Bilateral (left anodal/right cathodal): enhanced the generation of untruthful answers
[35] Feeser *et al.* (2013)	Right DLPFC	Anodal F4 / Cathodal contra. SO Sham (F4 / SO)	Online	20 min	1.5 mA	Anode: 35 cm^2 Cathode: 100 cm^2	Emotion regulation	**1** Right anodal: enhancement of performance (downregulation or upregulation of emotions)
[60] Foerster *et al.* (2013)	Left DLPFC	Anodal F3 / Cathodal contra. SO Sham (F3 / SO)	Online	13 min	2 mA	20 cm^2	Motor learning	**1** Left anodal: enhanced motor learning (motor-imagery-induced learning)

Authors	Target Region(s)	Montage	Timing of tDCS	Duration	Intensity	Electrode Size	Cognitive Domain	Cognitive effect
[47] Hoy *et al.* (2013)	Left DLPFC	Anodal F3 / Cathodal right SO Sham (F3 / SO)	Offline	20 min	1 mA and2 mA	35 cm^2	Working memory	**1** Left anodal: enhanced performance (both 1mA and 2mA)
[64] Iuculano and Cohen Kadosh (2013)	Left/Right DLPFC	Anodal F3 / Cathodal F4 Sham (F3/F4)	Online	20 min × 6 sessions	1 mA	3 cm^2	Learning and automaticity	**1** Bilateral: impaired numerical learning but enhanced automaticity for learned materials
[27] Javadi *et al.* (2013)	Left DLPFC	Anodal F3 / Cathodal contra. SO Cathodal F3 / Cathodal contra. SO Sham (F3 / SO)	Online	20 min	1.5 mA	Target: 12.2 cm^2 Reference: 30.2 cm^2	Long term memory	**1** Left anodal: enhanced memory performance (recognition)
[23] Kongthong *et al.* (2013)	Left DLPFC	Cathodal F3 / Anodal T6 Sham (F3/T6)	Offline	20 min	1 mA	25 cm^2	Visual semantic processes	**1** Left cathodal: decreased performance (elimination of priming effect)
[59] Manenti *et al.* (2013)	Left/Right DLPFC	Anodal F3 or F4 / Cathodal contra. SO Sham (F3 or F4 / SO)	Online	6 min	1.5 mA	35 cm^2	Verbal episodic memory	**1** Left and right anodal: increased memory performance in young subjects **2** Left anodal: increased memory performance in older subjects
[48] Meiron *et al.* (2013)	Left DLPFCRight DLPFC	Anodal F3 or F4 / Cathodal Cz Sham (F3 / Cz)	Online	15 min	2 mA	Anode: 16 cm^2 Cathode: 35 cm^2	Working memory	**1** Left anodal: improved performance (highest memory load males only) **2** Right anodal: improved performance (highest

Authors	Target Region(s)	Montage	Timing of tDCS	Duration	Intensity	Electrode Size	Cognitive Domain	Cognitive effect	
									memory load females only memory load females only
[32] Mengarelli *et al.* (2013)	Left DLPFCRight DLPFC	Cathodal F3 / Anodal contra SO Cathoal F4 / Anodal contra SO Sham (F3 or F4 / SO)	Online	15 min	1 mA	35 cm^2	Decision making	**1**	Left cathodal: reduced behaviour-induced preference change
[61] Motohashi *et al.* (2013)	Left DLPFC	Anodal F3 / Cathodal contra SO Sham (F3 / SO)	Offline	20 min	1 mA	35 cm^2	Mood	**1**	Left anodal: no sign. effect on mood
[68] Nozari *et al.* (2013)	Left/Right DLPFC	Anodal F3 / Cathodal F4 Sham (F3 / F4)	Online	20 min	1.5 mA	25 cm^2	Attention Language	**1**	Bilateral (left anodal/right cathodal): increased performance (verbal task)
[40] Plewnia *et al.* (2013)	Left DLPFC	Anodal F3 / Cathodal contra SO Sham (F3 / SO)	Online	20 min	1 mA	35 cm^2	Executive functions	**1**	Left anodal: no sign. effect for whole group but decreased performance for COMT Met-Met
[34] Tanoue *et al.* (2013)	Right DLPFC	Cathodal F4 / Anodal contra. cheek Sham (F4 / contra. cheek)	Offline	10 min	1.5 mA	35 cm^2	Attention	**1**	Right cathodal: impairs internal attention
[52] Vanderhasse *et al.* (2013)	Left DLPFC	Anodal F3 / Cathodal contra SO Sham (F3 / SO)	Online	20 min	2 mA	35 cm^2	Working memory Emotion processing	**1**	Left anodal: enhanced performance (working memory of angry faces)
[49] Vanderhasse *et al.* (2013)	Left DLPFC	Anodal F3 / Cathodal contra SO Sham (F3 / SO)	Offline	20 min	2 mA	35 cm^2	Emotion processing	**1**	Left anodal: enhanced cognitive control for positive stimuli
[30] Balconi *et al.* (2014)	Left DLPFC	Cathodal F3 / Anodal right SO	Offline	15 min	2 mA	35 cm^2	Semantic processing of actions	**1**	Left cathodal: modulated

Authors	Target Region(s)	Montage	Timing of tDCS	Duration	Intensity	Electrode Size	Cognitive Domain	Cognitive effect	
		Sham (F3/ Right SO)							performance (reduced RT to incorrect object use but increased errors rates)
[73] Nelson *et al*. (2014)	Right/LeftDLPFC	Anodal F3 / Cathodal F4 Cathodal F3 / Anodal F4 Sham (F3 / F4)	Online	10 min	1 mA	35 cm^2	Attention / Vigilance	**1**	Bilateral (anodal left/ cathodal right and anodal right / cathodal left): enhanced performance (detection task)

* Only main results were included in the present table.

** Presented results are restricted to the DLPFC. Results from an additional method of investigation (such as EEG) or an alternative region were not included.