Cathodal transcranial direct current stimulation over the right dorsolateral prefrontal cortex cancels out the cost of selective retrieval on subsequent analogical reasoning

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Abstract

Analogical reasoning involves mapping the relation between two concepts within a specific field into a new domain to selectively retrieve a possible solution. Neuroimaging studies have shown that both selective retrieval and reasoning by analogy are related to activity in prefrontal regions such as the dorsolateral prefrontal cortex (DLPFC). In the present study, we investigate the role of the right DLPFC in modulating memory accessibility and its impact on analogical reasoning by using transcranial direct current stimulation (tDCS). Participants performed a four-term reasoning task after performing repeated selective retrieval of previously presented items, some of which could be used as solutions in the analogical test. During selective retrieval, half of the participants received cathodal tDCS over the right DLPFC and the other half received sham stimulation. The results reveal that whereas the sham group showed the expected cost in performance that is associated with selective retrieval, the cathodal group did not exhibit such an impairment in reasoning. No general effects of tDCS on analogical performance were observed. Altogether, our results support the involvement of the right DLPFC as a core component of a control network that selectively contributes to the retrieval component of analogical reasoning, but with little role in mapping relations between different domains.

Keywords: Retrieval, Analogical Reasoning, Dorsolateral Prefrontal Cortex, Executive Control

1. Introduction

Many daily activities demand novel and innovative ideas and analogical reasoning may be useful to develop them (Green, Kraemer, Fugelsang, Gray, & Dunbar, 2012; Holyoak & Thagard, 1995). We often refer back to successful solutions that worked in the past when we try to find inspiration to solve a problem or explain an idea (Holyoak, 2012). There are many instances where analogical thinking led to inspirational ideas by binding concepts from different domains, such as the Velcro, which was based on a burr, or the blood circulation explanation that is based on a hydraulic system. Nevertheless, effective analogical problem solving might be difficult to reach (Gick & Holyoak, 1980; Trench & Minervino, 2015).

Research has demonstrated that people often fail to spontaneously transfer useful knowledge from memory (Gick & Holyoak, 1980; Gick & Holyoak, 1983). Analogical reasoning involves both controlled retrieval of the abstract relation between two concepts within a domain, and mapping this relation into the new domain to retrieve a possible solution. Hence, retrieval of information from memory and mapping this relation across domains seem to be two critical processes for successful analogical processing (Hummel & Holyoak, 1997). Some studies have shown that analogical transfer may be constraint by superficial and structural dissimilarity (Blanchette & Dunbar, 2000; Chen, Mo, & Honomichl, 2004; Dunbar, 2001), as well as lack of domain expertise (Catrambone, 2002; Novick, 1988). At the same time, analogical retrieval may fail when pertinent information is temporally inaccessible; that is, if relevant previous knowledge is not sufficiently activated, retrieval and recombination of ideas involving this knowledge

might be unlikely. Thus, retrieval dynamics may play a considerable role in influencing subsequent choices and leading to success in problem solving. In this sense, understanding how we retrieve knowledge during the analogical reasoning process can be particularly interesting.

In this line, recent work has explored whether information that is temporally less accessible would be more difficult to be selected as a potential solution in four-terms analogical problems (Valle, Gómez-Ariza, & Bajo, 2019). In order to modulate the accessibility of relevant information, Valle et al. (2019) introduced an adapted selective retrieval procedure (Anderson, Bjork, & Bjork, 1994) before an analogical reasoning test. In their experiments, participants first studied a list of orthography-based category-exemplars pairs (e.g. DE-Detective, DE-Democracy, FA-Fantasy, FA-Fatality), and right after they were asked to selectively retrieve half of the exemplars from half of the studied categories from recall cues (e.g. DE-Det____). By this, the accessibility of the retrieved items (e.g. Detective) was expected to increase, whereas the accessibility of related items (unpracticed words from practiced categories; e.g. Democracy) was expected to decrease (i.e., Anderson, 2003; for a meta-analytic review of the aftereffect of selective retrieval, see Murayama, Miyatsu, Buchli, & Storm, 2014). Finally, after a distractor task, participants were tested on their ability to solve a set of analogical thinking problems (e.g. FREEDOM is to SLAVERY as DICTATORSHIP is to …). Importantly, many of these analogies could be solved by using words that the participants studied previously. Results showed that non-retrieved words that were related to retrieved ones were less likely to be generated as appropriate solutions in analogical problems compared to control words. This reduced memory accessibility that follows selective retrieval may be explained as a consequence of an inhibitory control mechanism that acts over competing representations to downregulate their activation and to reduce interference (Weller, Anderson, Gómez-

Ariza, & Bajo, 2013; Wimber, Alink, Charest, Kriegeskorte, & Anderson, 2015). If the inhibited representations are later needed as possible solutions for the analogical problem, successful retrieval of these solutions will be reduced. In a similar vein, Gómez-Ariza et al. (2017a) used a similar approach to demonstrate that reducing the activation level of relevant information in memory may impair subsequent creative problem solving. Overall, these findings support the idea that reduced access to relevant information may unwittingly disrupt both analogical and creative problem solving. Importantly in the context of the resent study, these results also suggest that this procedure can be used to selectively render some information less accessible, and to mimic real-world situations where attempts to retrieve information may make some relevant information less retrievable.

Neuroimaging studies have shown that the lower accessibility of previously competing information that follows selective retrieval is related to activity in prefrontal regions such as the dorsolateral (DLPFC), ventrolateral (VLPFC) and anterior cingulate cortex (ACC) (Kuhl, Dudukovic, Kahn, & Wagner, 2007; Wimber et al., 2015; Wimber et al., 2008; Wimber, Rutschmann, Greenlee, & Bäuml, 2009). Kuhl et al. (2007) found that BOLD signal decreased in the right DLPFC and VLPFC over retrieval practice trials. Interestingly, subsequent forgetting of competitors correlated with reductions on prefrontal cortex demands during selective retrieval, and ACC activation correlated with the recruitment of the right DLPFC, which was related to the strengthening and facilitation of target memories.

Previous research has also shown that prefrontal regions play a critical role in analogical reasoning (for a review see Hobeika, Diard-Detoeuf, Garcin, Levy, & Volle, 2016). Many of these previous studies compared activation when solving four-term verbal analogies, which require relational integration, to semantic control conditions wherein participants

have to indicate whether two items are semantically related to each other. A consistent conclusion across studies is that the left rostrolateral prefrontal cortex (RLPFC) is specifically implicated in the mapping component (integration) of analogical reasoning (Bunge, Wendelken, Badre, & Wagner, 2005; Green, Fugelsang, & Dunbar, 2006; Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010; Green et al., 2012; Krawczyk, Mcclelland, Donovan, Tillman, & Maguire, 2010; Wendelken, Nakhabenko, Donohue, Carter, & Bunge, 2008), which is consistent with the involvement of this brain region in abstract information processing (Christoff, Ream, Geddes, & Gabrieli, 2003) and the integration of distinct relationships (Cho et al., 2010; Christoff et al., 2001). Along these lines, a recent meta-analysis of fMRI studies has showed that analogical reasoning across a variety of tasks involves a bilateral network that includes the above-mentioned left RLPFC (BA 10), the right insular area (BA 13) and, of special relevance here, the right DLPFC (BA 9, posterior parts of the inferior frontal gyrus/medial frontal gyrus) (Hobeika et al., 2016). While it seems clear that the right DLPFC would not mediate the analogical integration process itself (which has been specifically related to the left RLPFC), it seems to be recruited as part of a fronto-parietal control network that has been largely associated with complex cognition, such as reasoning and fluid intelligence (i.e., Prado, Chadha, & Booth, 2011; Reineberg, Andrews-Hanna, Depue, Friedman, & Banich, 2015; Wendelken, 2015), or working memory (i.e., Champod & Petrides, 2010). In a seminal work, Bunge et al. (2005) found that the activation of the right DLPFC during analogical reasoning was differentially engaged in a condition that involved the rejection of invalid analogies, which is consistent with the idea that this region is a core component of a inhibitory-like executive network (i.e., Cipolotti et al., 2016; Gagnepain, Henson, & Anderson, 2014; Gómez-Ariza, Martín, & Morales, 2017; Kelly et al., 2004; Shackman, McMenamin, Maxwell, Greischar, & Davidson, 2009; Zmigrod, Colzato, & Hommel,

2014) that could be also related to individual differences in analogical reasoning (Hammer et al., 2019). In this context, the present study aimed to shed light on the specific role of the right DLPFC in memory accessibility and its effect on analogical reasoning by using transcranial direct current stimulation (tDCS).

Although neuroimaging techniques have been very useful in suggesting the brain regions underlying the different processes involved in analogical reasoning and inhibitory control during retrieval, imaging data are correlational in nature and cannot provide causal links on which regions play a crucial role in these processes. In contrast, non-invasive brain stimulation techniques, such as tDCS, may be useful to test a causal hypothesis about the neural substrates that underlie cognition (Berryhill, Peterson, Jones, & Stephens, 2014; Bestmann, de Berker, & Bonaiuto, 2015; Filmer, Dux, & Mattingley, 2014). tDCS involves the application of a weak electrical current (usually 1-2 mA) through scalp electrodes to modulate neuron resting-state neuronal membrane potentials. Oversimplifying, at the neural level anodal tDCS is thought to increase the excitability whereas cathodal tDCS is thought to have the opposite effect, decreasing the excitability of the underlying neurons (Nitsche et al., 2008). Importantly, the excitability changes induced by this technique has been shown to last up to one hour (Nitsche et al., 2008), which may allow the temporary modulation of the functional contribution of prefrontal regions to cognitive and executive functions.

Recent tDCS findings support the involvement of prefrontal regions in the downregulation of competing memories during retrieval (J. F. I. Anderson, Davis, Fitzgerald, & Hoy, 2015; Penolazzi, Stramaccia, Braga, Mondini, & Galfano, 2014; Stramaccia, Penolazzi, Altoè, & Galfano, 2017). Thus, for example, Stramaccia et al. (2017) found that, relative to sham stimulation, anodal and cathodal tDCS over the right VLPFC eliminated the accessibility cost of selective retrieval, whereas Penolazzi et al.

(2014) found that participants did not exhibit such an impairment after cathodal tDCS of the right DLPFC. Therefore, these findings suggest that the prefrontal neuromodulation by tDCS may affect inhibitory control over information in memory. To our knowledge, however, no previous tDCS studies have explored the implication of the right DLPFC in reducing the accessibility of relevant information for analogical reasoning. Therefore, our aim in this study was to investigate the role of this region in regulating memory retrieval during analogical reasoning by using tDCS. With this purpose, we followed the procedure used by Valle et al. (2019) in Experiment 2. Specifically, and in order to minimize participants' awareness of the relation between the memory and reasoning tasks, analogies whose solution matched with practiced items (Rp+) were not presented. Hence, the only difference between this previous experiment and the one reported here concerns the delivery of tDCS during selective retrieval practice. Therefore, we presented participants with a series of category-exemplars pairs and asked them to selectively retrieve half of the exemplars from half of the categories during several rounds of trials. Critically, tDCS (cathodal vs. sham) was delivered during this phase of the experiment when inhibitory control is thought to be triggered (e.g., Kuhl et al., 2007; Román, Soriano, Gómez-Ariza, & Bajo, 2009; Wimber et al., 2015). Finally, participants were tested on their ability to solve four-term analogies whose solutions mostly matched with the words studied in their first phase. Based on prior fMRI research suggesting the role of the right DLPFC in downregulating memories (i.e., Kuhl et al., 2007; Wimber et al., 2009), and recent tDCS studies demonstrating that cathodal stimulation of the right DLPFC may temporarily disrupt its activity when exerting inhibitory-like control is needed (i.e., Friehs & Frings, 2019; Gómez-Ariza, Martín & Morales, 2017b; Penolazzi et al., 2014; Silas & Brandt, 2016; Zmigrod, Colzato, & Hommel, 2015), we expected cathodal tDCS to reduce the cost of selective retrieval on analogical reasoning. Hindering control during

retrieval, cathodal tDCS should increase the production of Rp- items as solutions in a subsequent analogical reasoning task when compared with the sham condition. Thus, while we expected sham stimulation to lead to retrieval-induced impairment in analogical performance (by replicating results reported by Valle et al. 2019), cathodal tDCS was expected to reduce or eliminate such an impairment. Our focus on cathodal rather than anodal stimulation was based on findings of related previous studies that showed anodal tDCS over the right lateral prefrontal cortex to have the largest (or only) effect on performance (Penolazzi et al., 2014; Stramaccia et al., 2017; but see Friehs & Frings, 2019, who observed enhanced inhibitory control of motor responses after anodal tDCS). Hence, and even though it could have been informative to incorporate anodal stimulation in our experiment, for the sake of simplicity we decided to include cathodal tDCS as the only real stimulation condition. In addition, and to the extent that the right DLPFC is not directly involved in integration (mapping) processes in analogical thinking (i.e., Bunge et al., 2005; Hammer et al., 2019; Hobeika et al., 2016), we did not expect cathodal tDCS to modulate performance for the control analogies (those to be solved with Nrp and Us items), which were not influenced by previous selective retrieval. Hence, the present experiment will help to dissociate the neural processes related to mapping and selective retrieval during analogical reasoning.

2. Methods

2.1. Participants

Based on the effect size (Rp- vs. Nrp; $d = .69$) observed in Valle et al. (2019; Experiment 2), which essentially used the same material and procedure as used here, we calculated the sample size for the present study by using G*Power 3.1 (Faul, Erdfelder, Buchner, & Lang, 2009). The analysis indicated that a sample of 20 participants per group was large

enough to detect a retrieval-induced impairment (power = 80%; alpha = 5%). Hence, 40 undergraduate psychology students (mean age = 23.43 years; SD = 5.98) were recruited to participate either for course credit or monetary reward. All participants had normal or corrected to normal sight, were right-handed as determined by the Edinburgh Handedness Inventory (Oldfield, 1971), and reported no history of psychiatric or neurological disorders, migraines, metallic implants, head injuries, seizures, epilepsy, and active medication apart from the contraceptive pill. The study was approved by the ethics committee of the University of Granada. Participants gave their informed consent prior to the start of the experiment and were naïve to the stimulation and hypothesis of the study. They were randomly assigned to the stimulation conditions.

2.2.Materials

The same set of items used by Gómez-Ariza et al. (2017a) and Valle et al. (2019) was employed here for the two first stages (encoding and retrieval practice) of the experiment. This material was composed of 54 items from nine different orthography-based categories (e.g. exemplars as Detective, Delito, Debate, Desastre, Deporte, and Democracia belonged to the orthographic category DE). These words could be used as practiced (Rp+) items, unpracticed items from practiced categories (Rp-) items, unpracticed-control (Nrp) items and unstudied (Us) items. The inclusion of Us items, which were never presented during the experimental session, would serve as an additional baseline condition to more precisely evaluate a) the extent to which Rp- items were made (or not, depending on the stimulation condition) less accessible as solutions during the problem-solving phase (Rp- vs. Us), and b) the 'priming' effect of having previously presented some items during the encoding phase (Nrp vs. Us). In addition, two more categories were used as fillers to control for primacy and recency effects. Each exemplar from a given category started

with their same two first letters but had a unique third letter. Taxonomic frequency of the exemplars was manipulated to ensure non-practiced items cause enough interference to trigger inhibition during retrieval practice. Thus, for each category, three exemplars were high-medium frequency words (range = 34–98, M= 58.78) selected to be used as Rp-, Nrp or Us items, and three low-medium frequency words (range = 10–36, M= 20.15) that were selected to be used as Rp+ items according to the Alameda and Cuetos Vega's (1995) norming database. Three different sets containing three of the nine categories were created (BA-DE-MA, CA-PE-FA, and DI-RE-TA) to counterbalance the material across participants, so that every category (and exemplar) appeared in every condition (Rp, Nrp and Us).

The analogical reasoning test comprised the same problems of the type 'A is to B as C is to …' used by Valle et al. (2019). Each analogy solution matched one of the 54 items described above (e.g. DEMOCRACY, which could be a solution for FREEDOM is to SLAVERY as DICTATORSHIP is to …). Analogies were to be solved by finding the relationship between pairs of words which might involve synonyms, antonyms, degree, sequences, part-wholes, cause and effect, association, purpose among others. In order to reduce the likelihood of producing a solution by semantic association of the 'C' term without applying analogical mapping strategies, the associative strength between the words corresponding to the 'C' term and the solution was controlled [forward (from the C item to the D item) and backward (from the D item to the C item) associative strength < .20) according to Spanish free association norms (Fernandez, Díez, & Alonso, 2014).

2.3.Transcranial Direct Current Stimulation

tDCS was delivered through a DC Brain Stimulator Plus (NeuroConn, Ilmenau, Germany) via a pair of saline-soaked surface sponge electrodes (35 cm^2). In the active

tDCS group a constant current of 2mA was delivered for up to 20 minutes with a 30 s fade-in and fade-out ramp. The cathodal electrode was positioned over F4 (right DLPFC) following the international 10–20 system procedure for EEG electrode placement. The anodal electrode was placed on the contralateral shoulder. In the sham group we used the same electrodes montage and current intensity, but the stimulation only lasted 30 s with an 8 s fade-in and fade-out ramp. Participants were never told about the stimulation condition they received.

2.4.Procedure

The experiment was carried out in a unique session that lasted approximately one hour, with a procedure similar to that used by Valle et al. (2019) that was adapted to accommodate the tDCS protocol. Right after participants gave informed written consent for the experiment, the electrodes montage was prepared without turning the stimulation on. A schematic representation of the experimental procedure is depicted in Figure 1. During encoding, participants were asked to pay attention to the orthography-based category and exemplar pairs. Each pair (36 items) was presented in the center of the screen for 5 s, with a 1-s interval between the items, twice in a pseudo-randomized order (72 total trials). Fillers were presented at the beginning and at the end of the list. Following this phase, participants received (either cathodal or Sham) tDCS. Since the retrieval practice phase lasted about 10 minutes, during the first 8 min of tDCS participants engaged in a filler visual search task. Right after this, the retrieval practice phase started and participants were required to selectively retrieve half of the item from half of the categories studied during the first phase (9 items). Every trial comprised the presentation of a category cue (e.g., DE) for 2 s, a 1 s interval, and a three-letter stem clue (e.g. Det___) for 5 s. Participants were instructed to come up with the only studied word

that matched the stem. Each practice trial was presented three times in random blocks so that one item of each category was practiced at a time. After retrieval practice, participants solved arithmetical operations until the (20 min) period of tDCS was over. Right then, the analogical reasoning task was administered. Participants were explained that they would have to solve analogies of the type 'A is to B as C is to ?' by finding the relationship between 'A' and 'B' and transfer it to 'C' and '?'. They were also explained that the relationship might involve synonyms, antonyms, degree, sequences, part-wholes, cause and effect, association, purpose among others. Two practiced examples of analogies were presented and feedback was provided in order to get participants familiar with the task. Then, 27 analogy problems were shown at the center of the screen for up to 60 s or until the participant pulsed the space bar and made his/her response. To avoid output interference effects and reduce participants' awareness of the possibility of solving the analogies with practiced (Rp+) items from the previous phase, the reasoning task did not include problems to be solved with these items (see also Experiment 2 from Valle et al., 2019). Therefore, one only block containing analogies whose solutions corresponded with the unpracticed (Rp-), unpracticed control (Nrp) and unstudied (Us) items was presented (see Valle et al., 2019). The nine experimental categories were divided into three different sets (BA-DE-MA, CA-PE-FA and DI-RE-FA) to create three counterbalance conditions of practiced (Rp+/- items), unpracticed control (Nrp items) or unstudied (Up- items) categories. These sets were matched for difficulty level (see Valle et al. 2019). In summary, then, each solution to the analogies appeared equally in every practice/study condition as Rp-, Nrp and Us (9 items per condition). Note that the participants were naïve with respect to the purpose of the study and were told they would carry out different experiments not related to them. To examine whether participants were aware of the relationship between both tasks and retrieval strategies, a post-task questionnaire was

administered. Finally, at the end of the experimental session participants completed a questionnaire on tDCS adverse effects (Brunoni et al., 2011). No one participant reported significant discomfort associated with stimulation.

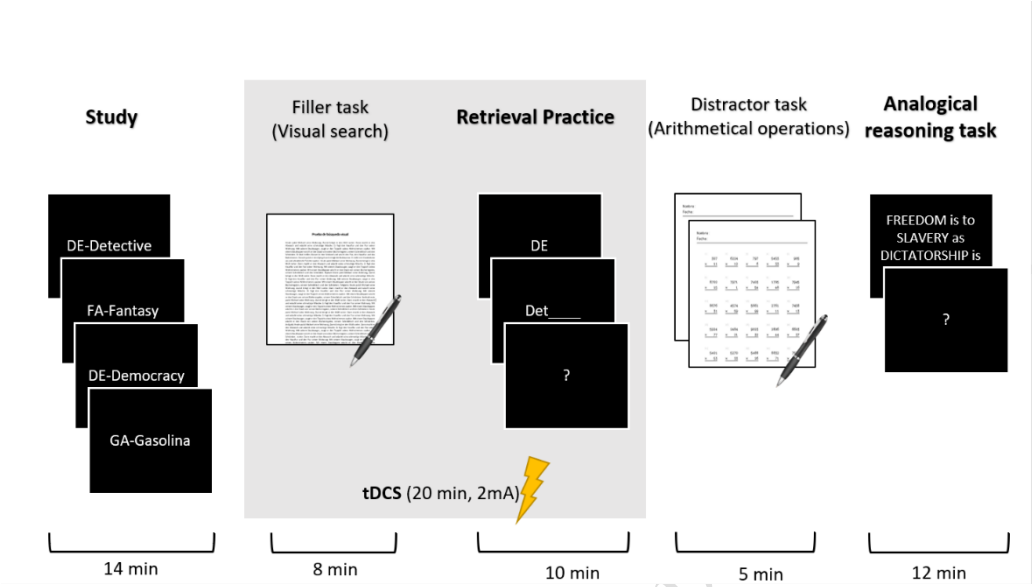

Figure 1. Schematic representation of the experimental procedure showing the timing of the tasks.

3. Results

On average, the percentage of correct recall during the practice phase was 55% (SD = 21.06). Mean recall during this phase did not differ significantly between sham and cathodal stimulation groups (M_{sham} = 52.59, SD_{sham} = 21.61; $M_{cathodal}$ = 57.40, $SD_{cathodal}$ = 20.76; $t(38)$= -.718, p = .48, d = .23). The mean percentage of successfully solved analogies was 50.94% (SD = 17.79), with the difference between the two stimulation groups being close to the conventional level of statistical significance (M_{sham} = 45.59, SD_{sham} = 12.35; $M_{cathodal}$ = 56.30, $SD_{cathodal}$ = 20.90; $t(38)$= -1.98, p = .06, d = .62). None of the participants reported being aware of the relation between the memory and the

analogy tasks. Figure 2 shows performance on the analogical reasoning test as a function of stimulation condition and type of item.

Retrieval-induced impairment effect. A 2 (cathodal tDCS vs. Sham) x 2 (Rp- vs. Nrp) mixed analysis of variance (ANOVA) was performed to examine the impact of tDCS on analogical reasoning performance. A main effect of type of item revealed that Rp- items (M = 46.67; SD = 3.04) were significantly less generated as solutions than Nrp control items (M = 55.83; SD = 2.38), $F(1,38) = 11.06$, $MSE = 1680.56$, $p < .01$, $\eta_p^2 = .23$. A main effect of stimulation was also found, $F(1,38) = 5.85$, $MSE = 2594.14$, $p = .02$, $\eta_p^2 = .13$, indicating that those participants who received cathodal tDCS (M = 56.94; SD = 3.33) solved more analogies than those from the sham condition (M = 45.56; SD = 3.33). More relevant, there was a reliable interaction between type of item and stimulation, $F(1,38) = 7.40$, $MSE = 1125.00$, $p = .01$, $\eta_p^2 = .16$. Planned comparisons showed that while the sham group solved less analogies with Rp- than Nrp items $t(19) = -4.68$, $p < .01$, $d = 1.05$, so exhibiting a retrieval-induced impairment, this effect was not present in the cathodal group $t(19) < 1$, $p = .70$, $d = .09$. The lack of effect in the cathodal group did not seem to result from baseline deflation, since the two groups exhibited similar performance when solving analogies with Nrp items ($t(38) = -.817$, $p = .42$, $d = .26$).

Priming effect. We also explored whether tDCS modulated the effect of presenting the potential solutions to the problems during the study phase when ruling out the effect of retrieval practice (Valle et al., 2019). A 2 (cathodal tDCS vs. Sham) x 2 (Nrp vs. Us) ANOVA showed a main effect of type of item, $F(1,38) = 4.96$, $MSE = 1365.84$, $p = .03$, $\eta_p^2 = .12$., which confirms that participants solved more analogies with previously presented items. However, tDCS did not modulate analogical reasoning performance on these problems (main effect: $F(1,38) = 1.27$, $MSE = 291.76$, $p = .27$, $\eta_p^2 = .03$; interaction: $F(1,38) < 1$, $MSE = .10$, $p = .99$, $\eta_p^2 = .00$.

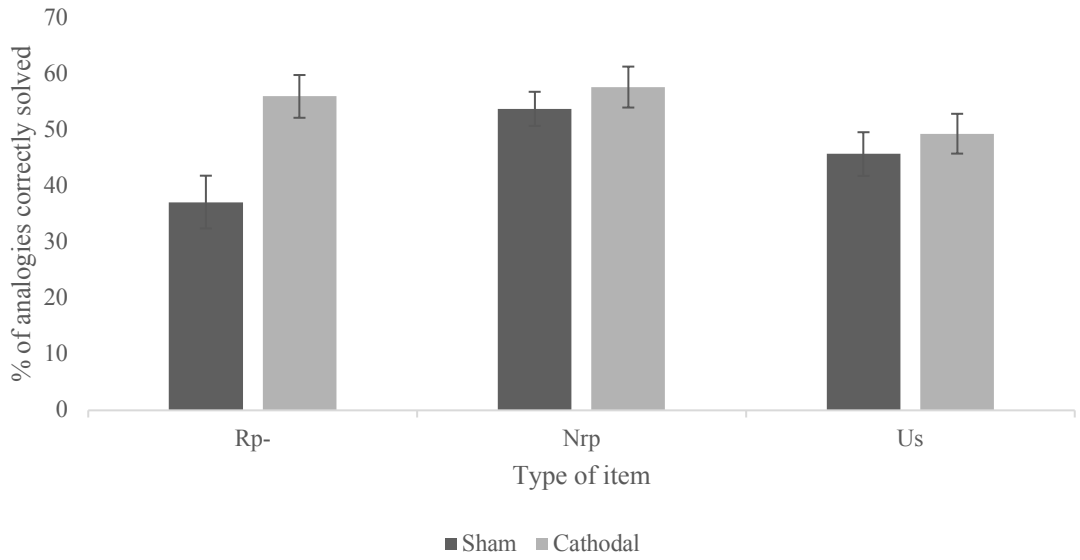

Figure 2. Performance on the analogical reasoning test as a function of stimulation and type of item. Rp- = Unpracticed solutions from practiced categories that competed for retrieval during practice; Nrp = Unpracticed (control) solutions from non-practiced categories; Us = Unstudied (control) solutions that were never presented in the context of the experiment.

4. Discussion

Over the last decade, research has explored the role of LPFC in cognitive control, memory, and reasoning. Nevertheless, the neural substrates and cognitive mechanisms that underpin the memory-reasoning interaction has been traditionally addressed by different lines of research with relatively little effort made to examine the joint involvement of the two domains (Green, Fugelsang, Kraemer, Shamosh, & Dunbar, 2006; Green et al., 2010, 2012; Wimber et al., 2008, 2009). This interaction is, however, critical

since memory retrieval and mapping are important components of analogical reasoning (Hummel & Holyoak, 1997).

In the present study, we focused on this relation by investigating the role of the right DLPFC in modulating memory accessibility and its impact on analogical reasoning by using tDCS. Previous research has shown that a) activity in this prefrontal region is related to downregulation of competing information during retrieval (Kuhl et al., 2007; Wimber et al., 2015, 2008, 2009) as well as to control requirements in analogical reasoning (Bunge et al., 2005), b) retrieval of relevant information is a core component of analogical reasoning, and c) cathodal tDCS over the right DLPFC compromises interference control (Friehs & Frings, 2019; Gómez-Ariza et al., 2017b; Penolazzi et al., 2014; Zmigrod et al., 2014). Hence, in our experiment we compared the offline effects of cathodal and sham tDCS over the right DLPFC on performance in a four-term analogical reasoning task. Critically, participants performed the reasoning task after performing selective retrieval of previously presented items, some of which could be used as solutions in the analogical test. Selective retrieval should lead to reduced accessibility of related but non-retrieved competing information (for a meta-analytic review of the effects of selective retrieval see Murayama et al., 2014). Since controlled retrieval and mapping are assumed to be two dissociable components of analogical reasoning (Hummel & Holyoak, 1997), we expected that cathodal tDCS over the right prefrontal cortex would selectively modulate retrieval. Thus, we predicted that the sham group would show lower production of Rp- solutions relative to Nrp solutions when it came to solving four-term analogies, whereas cathodal tDCS was expected to eliminate this effect by altering activity in the right DLPFC (and likely connected regions). In addition, and to the extent that the role of this region is not central to the integration (mapping) component of analogical thinking (i.e.,

Bunge et al., 2005; Hammer et al., 2019; Hobeika et al., 2016), no general effects of tDCS on analogical performance were predicted.

Consistent with these predictions, we observed reduced accessibility to Rp- solutions relative to the Nrp items in the sham group, indicating that the usual more difficult access to inhibited information was present in this condition. Critically, this effect was not present in the cathodal group and Rp- items were produced as solutions to the same extent than Nrp items, suggesting that control at retrieval had been disrupted and this affected performance in the analogical task. Since lower production of Rp- (relative to Nrp) solutions may be interpreted as the aftereffect of interference control during retrieval (Kuhl et al., 2007; Penolazzi et al., 2014; Román et al., 2009; Wimber et al., 2015), the fact that cathodal tDCS canceled out this effect suggests that stimulating the right lateral prefrontal cortex disrupted the normal activity in this area. Importantly, no other effect of tDCS was evident from the participants' behavior. Accuracy during retrieval practice (tDCS online) was similar in both groups, and no differences in analogical reasoning performance emerged when participants had to find solutions to analogies that could be solved with control (Nrp and Us) items, which were unrelated to those that were previously recalled.

A straightforward interpretation of the present findings is that cathodal tDCS hindered the downregulation of competing (Rp-) items during selective retrieval, which allowed participants from this group to have regular access to their representations during the reasoning task. Retrieval is necessarily a core component of analogical thinking because the relation between the relevant domains needs to be identified and retrieved from memory as it needs to be the solution to be produced after mapping this relation into the new domain (Bunge et al., 2005; Gentner & Smith, 2012; Hummel & Holyoak, 1997). Thus, the present results support this idea by showing that influencing how accessible

potential solutions are (either as a consequence of previous recall attempts or as a result of modulating brain activity) has an effect on performance during analogical problem solving. In addition, our results support the involvement of the right DLPFC as a core component of a control network that contributes to retrieval and align with results from neuroimaging (Kuhl et al., 2007; Wimber et al., 2008, 2009, 2015) and neuromodulation studies (Penolazzi et al., 2014) that point to the right (dorsal and ventral) lateral prefrontal cortex as a source of topdown control of retrieval processes. To this respect, it is important to note that in the present study the size of the electrodes was larger (3x7 cm vs. 4x4 cm) than in previous tDCS experiments that aimed to modulate inhibitory control during selective retrieval (Penolazzi et al., 2014; Stramaccia et al., 2017). Hence, we cannot exclude the possibility that the active cathodal electrode may have influenced brain areas surrounding the right DLPFC (i.e., VLPFC) and that are also part of the inhibitory network (Kuhl et al., 2007; Wimber et al., 2015). Nevertheless, what is important here is that the present findings support the causal involvement of the right lateral prefrontal cortex in modulating memory accessibility.

It is worth noting that we did not observe a general effect of tDCS on analogical reasoning, given that the Nrp and Us solutions were produced to the same extent in the two stimulation groups. This suggests that the mapping/integration process required to make transfer between domains was not affected by cathodal stimulation over the right DLPFC. While neuroimaging studies that explored the contribution of the prefrontal cortex to analogical reasoning have shown some involvement of this region (Hobeika et al., 2016 for a meta-analysis; but see Hammer et al., 2019), its role has been more generally linked to retrieval related control processes (i.e., Bunge et al., 2005; Cho et al., 2010). Thus, for example, Bunge et al. (2005) found that activity in the right DLPFC was significantly greater when their participants were to refrain from accepting invalid

responses to analogies, which they interpreted in terms of response selection, and Cho et al. (2010) found that a cluster in the right lateral PFC was sensitive to the need to dismiss distracting information during retrieval in analogical reasoning. Hence, one could think of interference control as a component of analogical reasoning to prevent salient but misleading information from influencing responses, with the right DLPFC most likely playing a role in this regard. However, since neither our four-term analogies were specifically created to greatly require interference control (rather, they were made so that some of them could be solved with previously studies items), nor we manipulated interference conditions during the final stage of analogical reasoning (instead, interference control was to be recruited during selective retrieval), cathodal tDCS was not predicted to globally modulate performance during problem solving. Recent fMRI (Hobeika et al., 2016) and tDCS (Green et al., 2017) studies have linked the left RLPFC to the relational integration required by analogical thinking. Hence, while the left RLPFC seems to be related to mapping processes, the right DLPFC might be involved in retrieval control.

Finally, it is important to note that the pattern of performance observed in the sham group replicates the cost that selective retrieval may have on problem solving and decision making (Gómez-Ariza et al., 2017a; Iglesias-Parro & Gómez-Ariza, 2006; Valle et al., 2019) and entitled us to use this group's performance as a baseline. In addition, the fact that the cathodal group did not exhibit such a decrease in accessibility of the Rp- items essentially replicates results from Penolazzi et al. (2014), who observed that cathodal tDCS over the right DLPFC eliminated the cost of selective retrieval in a memory task. However, it is important to note that some differences exist between the present experiment and that one by Penolazzi et al., (2014). First, they used an explicit memory test to investigate the causal involvement of the DLPFC in retrieval-induced forgetting.

Our study, however, show that the outcome of disrupting the activity of the right lateral prefrontal cortex during selective retrieval may be also observed in the context of problem solving and without awareness of episodic recall. Also, while Penolazzi et al. (2014) used a cephalic montage (supraorbital area) for the reference electrode, in the current study the reference electrode was placed extracephalically (on the contralateral shoulder) in order to minimize its effect on the brain (Noetscher, Yanamadala, Makarov, & Pascual-Leone, 2014). Hence, the electrode montage employed here would seem to have genuinely targeted the right lateral prefrontal cortex, which, in principle, allow us to rule out the possibility that an unbalance in interhemispheric dynamics could have influenced the present findings. Therefore, ours clarify previous results by providing evidence that the expected disruption of retrieval control (to selectively impact on competing items) can be obtained by means of cathodal tDCS over the right DLPFC (with the reference electrode placed extracephalically).

To conclude, the present study provides causal evidence of the involvement of the right lateral prefrontal cortex in the retrieval component regulating memory accessibility during analogical reasoning. Our results also show that tDCS can be used to examine the contribution of cognitive control to thinking. Cathodal tDCS over the right DLPFC disrupted interference control during retrieval affecting, thus, analogical reasoning. Future neuromodulation studies should include experimental manipulations to further clarify the involvement of this region in retrieval during analogical reasoning. The combination of neuromodulation techniques and neural signal measurements (i.e., fMRI or EEG) will also help to this end.

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References

Alameda, J. R., & Cuetos, F. (1995). *Diccionario de frecuencias de las unidades lingüísticas del castellano [Dictionary of the frequencies of linguistic units in Spanish]*. Oviedo: Servicio de Publicaciones de la Universidad de Oviedo.

Anderson, J. F. I., Davis, M.-C., Fitzgerald, P. B., & Hoy, K. E. (2015). Individual differences in retrieval-induced forgetting affect the impact of frontal dysfunction on retrieval-induced forgetting. *Journal of Clinical and Experimental Neuropsychology*, *37*(2), 140–151. https://doi.org/10.1080/13803395.2014.993307

Anderson, M. C. (2003). Rethinking interference theory: Executive control and the mechanisms of forgetting. *Journal of Memory and Language*, *49*(4), 415–445. https://doi.org/10.1016/j.jml.2003.08.006

Anderson, M. C., Bjork, R. A., & Bjork, E. L. (1994). Remembering Can Cause Forgetting - Retrieval Dynamics in Long-Term-Memory. *Journal of Experimental Psychology: Learning Memory and Cognition*, *20*(5), 1063–1087. https://doi.org/10.1037/0278-7393.20.5.1063

Berryhill, M. E., Peterson, D. J., Jones, K. T., & Stephens, J. A. (2014). Hits and misses: leveraging tDCS to advance cognitive research. *Frontiers in Psychology*, *5*, 800. https://doi.org/10.3389/fpsyg.2014.00800

Bestmann, S., de Berker, A. O., & Bonaiuto, J. (2015). Understanding the behavioural consequences of noninvasive brain stimulation. *Trends in Cognitive Sciences*, *19*(1), 13–20. https://doi.org/10.1016/J.TICS.2014.10.003

Blanchette, I., & Dunbar, K. (2000). How Analogies are Generated: The Roles of Structural and Superficial Similarity. *Memory & Cognition*, *28*(1), 108–124. https://doi.org/10.3758/BF03211580

Brunoni, A. R., Amadera, J., Berbel, B., Volz, M. S., Rizzerio, B. G., & Fregni, F. (2011). A systematic review on reporting and assessment of adverse effects associated with transcranial direct current stimulation. *International Journal of Neuropsychopharmacology*, *14*(8), 1133–1145. https://doi.org/10.1017/S1461145710001690

Bunge, S. A., Wendelken, C., Badre, D., & Wagner, A. D. (2005). Analogical Reasoning and Prefrontal Cortex: Evidence for Separable Retrieval and Integration Mechanisms. *Cerebral Cortex*, *15*(3), 239–249. https://doi.org/10.1093/cercor/bhh126

Catrambone, R. (2002). The effects of surface and structural feature matches on the access of story analogs. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *28*(2), 318–334. https://doi.org/10.1037/0278-7393.28.2.318

Champod, A. S., & Petrides, M. (2010). Dissociation within the frontoparietal network in verbal working memory: A parametric functional magnetic resonance imaging study. *Journal of Neuroscience*, *30*(10), 3849–3856. https://doi.org/10.1523/JNEUROSCI.0097-10.2010

Chen, Z., Mo, L., & Honomichl, R. (2004). Having the Memory of an Elephant: Long-Term Retrieval and the Use of Analogues in Problem Solving. *Journal of Experimental Psychology: General*, *133*(3), 415–433. https://doi.org/10.1037/0096-3445.133.3.415

Cho, S., Moody, T. D., Fernandino, L., Mumford, J. A., Poldrack, R. A., Cannon, T. D., … Holyoak, K. J. (2010). Common and Dissociable Prefrontal Loci Associated with Component Mechanisms of Analogical Reasoning. *Cerebral Cortex*, *20*(3), 524–533. https://doi.org/10.1093/cercor/bhp121

Christoff, K., Prabhakaran, V., Dorfman, J., Zhao, Z., Kroger, J. K., Holyoak, K. J., & Gabrieli, J. D. E. (2001). Rostrolateral Prefrontal Cortex Involvement in Relational Integration during Reasoning. *NeuroImage*, *14*, 1136–1149. https://doi.org/10.1006/nimg.2001.0922

Christoff, K., Ream, J. M., Geddes, L. P. T., & Gabrieli, J. D. E. (2003). Evaluating Self-Generated Information: Anterior Prefrontal Contributions to Human Cognition. *Behavioral Neuroscience*, *117*(6), 1161–1168. https://doi.org/10.1037/0735-7044.117.6.1161

Cipolotti, L., Spanò, B., Healy, C., Tudor-Sfetea, C., Chan, E., White, M., … Bozzali, M. (2016). Inhibition processes are dissociable and lateralized in human prefrontal cortex. *Neuropsychologia*, *93*, 1–12. https://doi.org/10.1016/j.neuropsychologia.2016.09.018

Dunbar, K. (2001). The analogical paradox: Why analogy is so easy in naturalistic settings, yet so difficult in the psychological laboratory. In D. Gentner, K. J. Holyoak, & B. N. Kokinov (Eds.), *Analogy: Perspectives from Cognitive Science* (pp. 313–334). Cambridge, MA: MIT Press.

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, *41*(4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149

Fernandez, A., Díez, E., & Alonso, M. Á. (2014). Normas de Asociacion libre en castellano de la Universidad de Salamanca [The University of Salamanca free association norms for Spanish; Online database].

Filmer, H. L., Dux, P. E., & Mattingley, J. B. (2014). Applications of transcranial direct current stimulation for understanding brain function. *Trends in Neurosciences*, *37*(12), 742–753. https://doi.org/10.1016/j.tins.2014.08.003

Friehs, M. A., & Frings, C. (2019). Cathodal tDCS increases stop-signal reaction time. *Cognitive, Affective, & Behavioral Neuroscience*. https://doi.org/10.3758/s13415-019-00740-0

Gagnepain, P., Henson, R. N., & Anderson, M. C. (2014). Suppressing unwanted memories reduces their unconscious influence via targeted cortical inhibition. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(13), E1310-9. https://doi.org/10.1073/pnas.1311468111

Gentner, D., & Smith, L. (2012). Analogical Reasoning. In V. S. Ramachandran (Ed.), *Encyclopedia of Human Behavior* (2nd Ed., pp. 130–136). Oxford, UK: Elsevier. https://doi.org/10.1016/B978-0-12-375000-6.00022-7

Gick, M. L., & Holyoak, K. J. (1980). Analogical Problem Solving. *Cognitive Psychology*, *12*, 306–355. https://doi.org/10.1016/0010-0285(80)90013-4

Gick, M. L., & Holyoak, K. J. (1983). Schema Induction and Analogical Transfer. *Cognitive Psychology*, *15*, 1–38. https://doi.org/10.1016/0010-0285(83)90002-6

Gómez-Ariza, C. J., Martín, M. C., & Morales, J. (2017). Tempering proactive cognitive control by transcranial direct current stimulation of the right (but not the

left) lateral prefrontal cortex. *Frontiers in Neuroscience*, *11*(MAY), 1–12. https://doi.org/10.3389/fnins.2017.00282

Gómez-Ariza, C. J., Prete, F., Prieto, L., Valle, T., Bajo, M. T., & Fernandez, A. (2017). Memory Inhibition as a Critical Factor Preventing Creative Problem Solving. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *43*(6), 986–996. https://doi.org/10.1037/xlm0000348

Green, A. E., Fugelsang, J. A., Kraemer, D. J. M., Shamosh, N. A., & Dunbar, K. N. (2006). Frontopolar cortex mediates abstract integration in analogy. *Brain Research*, *1096*(1), 125–137. https://doi.org/10.1016/j.brainres.2006.04.024

Green, A. E., Fugelsang, J. a, & Dunbar, K. N. (2006). Automatic activation of categorical and abstract analogical relations in analogical reasoning. *Memory & Cognition*, *34*(7), 1414–1421. https://doi.org/10.3758/BF03195906

Green, A. E., Kraemer, D. J. M., Fugelsang, J. A., Gray, J. R., & Dunbar, K. N. (2010). Connecting long distance: Semantic distance in analogical reasoning modulates frontopolar cortex activity. *Cerebral Cortex*, *20*(1), 70–76. https://doi.org/10.1093/cercor/bhp081

Green, A. E., Kraemer, D. J. M., Fugelsang, J. A., Gray, J. R., & Dunbar, K. N. (2012). Neural correlates of creativity in analogical reasoning. *Journal of Experimental Psychology: Learning Memory and Cognition*, *38*(2), 264–272. https://doi.org/10.1037/a0025764

Green, A. E., Spiegel, K. A., Giangrande, E. J., Weinberger, A. B., Gallagher, N. M., & Turkeltaub, P. E. (2017). Thinking Cap Plus Thinking Zap: tDCS of Frontopolar Cortex Improves Creative Analogical Reasoning and Facilitates Conscious Augmentation of State Creativity in Verb Generation. *Cerebral Cortex*, *27*, 2628–2639. https://doi.org/10.1093/cercor/bhw080

Hammer, R., Paul, E. J., Hillman, C. H., Kramer, A. F., Cohen, N. J., & Barbey, A. K. (2019). Individual differences in analogical reasoning revealed by multivariate task-based functional brain imaging. *NeuroImage*, *184*, 993–1004. https://doi.org/10.1016/j.neuroimage.2018.09.011

Hobeika, L., Diard-Detoeuf, C., Garcin, B., Levy, R., & Volle, E. (2016). General and specialized brain correlates for analogical reasoning: A meta-analysis of functional imaging studies. *Human Brain Mapping*, *37*(5), 1953–1969. https://doi.org/10.1002/hbm.23149

Holyoak, K. J. (2012). Analogy and Relational Reasoning. In K. J. Holyoak & R. G. Morrison (Eds.), *The Oxford handbook of thinking and reasoning* (pp. 234–259). New York: Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199734689.013.0013

Holyoak, K. J., & Thagard, P. (1995). *Mental leaps: Analogy in creative thought*. MA, Cambridge: MIT Press.

Hummel, J. E., & Holyoak, K. J. (1997). Distributed Representations of Structure: A Theory of Analogical Access and Mapping. *Psychological Review*, *104*(3), 427–466. https://doi.org/10.1037/0033-295X.104.3.427

Iglesias-Parro, S., & Gómez-Ariza, C. J. (2006). Biasing decision making by means of retrieval practice. *European Journal of Cognitive Psychology*, *18*(6), 899–908. https://doi.org/10.1080/09541440500501189

Kelly, A. M. C., Hester, R., Murphy, K., Javitt, D. C., Foxe, J. J., & Garavan, H. (2004). Prefrontal-subcortical dissociations underlying inhibitory control revealed by event-related fMRI. *European Journal of Neuroscience*, *19*(11), 3105–3112. https://doi.org/10.1111/j.0953-816X.2004.03429.x

Krawczyk, D. C., Mcclelland, M. M., Donovan, C. M., Tillman, G. D., & Maguire, M. J. (2010). An fMRI investigation of cognitive stages in reasoning by analogy. *Brain Research*, *1342*, 63–73. https://doi.org/10.1016/j.brainres.2010.04.039

Kuhl, B. A., Dudukovic, N. M., Kahn, I., & Wagner, A. D. (2007). Decreased demands on cognitive control reveal the neural processing benefits of forgetting. *Nature Neuroscience*, *10*(7), 908–914. https://doi.org/10.1038/nn1918

Murayama, K., Miyatsu, T., Buchli, D., & Storm, B. C. (2014). Forgetting as a consequence of retrieval: A meta-analytic review of retrieval-induced forgetting. *Psychological Bulletin*, *140*(5), 1383–1409. https://doi.org/10.1037/a0037505

Nitsche, M. A., Cohen, L. G., Wassermann, E. M., Priori, A., Lang, N., Antal, A., … Pascual-Leone, A. (2008). Transcranial direct current stimulation: State of the art 2008. *Brain Stimulation*, *1*(3), 206–223. https://doi.org/10.1016/j.brs.2008.06.004

Noetscher, G. M., Yanamadala, J., Makarov, S. N., & Pascual-Leone, A. (2014). Comparison of cephalic and extracephalic montages for transcranial direct current stimulation--a numerical study. *IEEE Transactions on Bio-Medical Engineering*, *61*(9), 2488–2498. https://doi.org/10.1109/TBME.2014.2322774

Novick, L. R. (1988). Analogical transfer, problem similarity, and expertise. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *14*(3), 510–520. https://doi.org/10.1037/0278-7393.14.3.510

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*. https://doi.org/10.1016/0028-3932(71)90067-4

Penolazzi, B., Stramaccia, D. F., Braga, M., Mondini, S., & Galfano, G. (2014). Human memory retrieval and inhibitory control in the brain: beyond correlational evidence. *The Journal of Neuroscience*, *34*(19), 6606–6610. https://doi.org/10.1523/JNEUROSCI.0349-14.2014

Prado, J., Chadha, A., & Booth, J. R. (2011). The brain network for deductive reasoning: A quantitative meta-analysis of 28 neuroimaging studies. *Journal of Cognitive Neuroscience*, *23*(11), 3483–3497. https://doi.org/10.1162/jocn_a_00063

Reineberg, A. E., Andrews-Hanna, J. R., Depue, B. E., Friedman, N. P., & Banich, M. T. (2015). Resting-state networks predict individual differences in common and specific aspects of executive function. *NeuroImage*, *104*, 69–78. https://doi.org/10.1016/j.neuroimage.2014.09.045

Román, P., Soriano, M. F., Gómez-Ariza, C. J., & Bajo, M. T. (2009). Retrieval-Induced Forgetting and Executive Control. *Psychological Science*, *20*(9), 1053–1058. https://doi.org/10.1111/j.1467-9280.2009.02415.x

Shackman, A. J., McMenamin, B. W., Maxwell, J. S., Greischar, L. L., & Davidson, R. J. (2009). Right dorsolateral prefrontal cortical activity and behavioral inhibition. *Psychological Science*, *20*(12), 1500–1506. https://doi.org/10.1111/j.1467-9280.2009.02476.x

Silas, J., & Brandt, K. R. (2016). Frontal transcranial direct current stimulation (tDCS) abolishes list-method directed forgetting. *Neuroscience Letters*, *616*, 166–169.

https://doi.org/10.1016/j.neulet.2016.01.035

Stramaccia, D. F., Penolazzi, B., Altoè, G., & Galfano, G. (2017). TDCS over the right inferior frontal gyrus disrupts control of interference in memory: A retrieval-induced forgetting study. *Neurobiology of Learning and Memory*, *144*, 114–130. https://doi.org/10.1016/j.nlm.2017.07.005

Trench, M., & Minervino, R. A. (2015). The Role of Surface Similarity in Analogical Retrieval: Bridging the Gap Between the Naturalistic and the Experimental Traditions. *Cognitive Science*, *39*(6), 1292–1319. https://doi.org/10.1111/cogs.12201

Valle, T. M., Gómez-Ariza, C. J., & Bajo, M. T. (2019). Inhibitory control during selective retrieval may hinder subsequent analogical thinking. *PLoS ONE*, *14*(2), 1–19. https://doi.org/10.1371/ journal.pone.0211881

Weller, P. D., Anderson, M. C., Gómez-Ariza, C. J., & Bajo, M. T. (2013). On the status of cue independence as a criterion for memory inhibition: evidence against the covert blocking hypothesis. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*(4), 1232–1245. https://doi.org/10.1037/a0030335

Wendelken, C. (2015). Meta-analysis: how does posterior parietal cortex contribute to reasoning? *Frontiers in Human Neuroscience*, *8*. https://doi.org/10.3389/fnhum.2014.01042

Wendelken, C., Nakhabenko, D., Donohue, S. E., Carter, C. S., & Bunge, S. A. (2008). "Brain is to thought as stomach is to ??": Investigating the role of rostrolateral prefrontal cortex in relational reasoning. *Journal of Cognitive Neuroscience*, *20*(4), 682–693. https://doi.org/10.1162/jocn.2008.20055

Wimber, M., Alink, A., Charest, I., Kriegeskorte, N., & Anderson, M. C. (2015). Retrieval induces adaptive forgetting of competing memories via cortical pattern suppression. *Nature Neuroscience*, *18*(4), 582–589. https://doi.org/10.1038/nn.3973

Wimber, M., Bäuml, K.-H., Bergström, Z., Markopoulos, G., Heinze, H.-J., & Richardson-Klavehn, A. (2008). Neural Markers of Inhibition in Human Memory Retrieval. *The Journal of Neuroscience*, *28*(50), 13419–13427. https://doi.org/10.1523/JNEUROSCI.1916-08.2008

Wimber, M., Rutschmann, R. M., Greenlee, M. W., & Bäuml, K.-H. (2009). Retrieval from episodic memory: neural mechanisms of interference resolution. *Journal of Cognitive Neuroscience*, *21*(3), 538–549. https://doi.org/10.1162/jocn.2009.21043

Zmigrod, S., Colzato, L. S., & Hommel, B. (2014). Evidence for a role of the right dorsolateral prefrontal cortex in controlling stimulus-response integration: A transcranial direct current stimulation (tDCS) study. *Brain Stimulation*, *7*(4), 516–520. https://doi.org/10.1016/j.brs.2014.03.004

Zmigrod, S., Colzato, L. S., & Hommel, B. (2015). Stimulating Creativity: Modulation of Convergent and Divergent Thinking by Transcranial Direct Current Stimulation (tDCS). *Creativity Research Journal*, *27*(4), 353–360. https://doi.org/10.1080/10400419.2015.1087280