Doctoral Dissertation

Accessibility and memory control during analogical problem solving

(Accesibilidad y control de la memoria durante la resolución de problemas de razonamiento analógico)

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Introductory Note

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Contents

Preface

One of the most astonishing qualities of human memory is its virtually unlimited capacity to store large amounts of information. This allows novel events to bring to mind remote ideas and experiences that might have been thought, known or perceived in the past, even though they have never been directly related to the remembered ones (Baddeley, Eysenck, & Anderson, 2015). The ability to reach logical conclusions and connect remote associations on the basis of prior information is central to human cognition (Holyoak, Gentner, & Kokinov, 2001). Namely, solving problems often requires thinking about experiences or solutions that turned out to be effective in the past as well as identifying new associations between concepts that seemed unrelated at first sight. A large number of creative discoveries have resulted from the application of knowledge about a familiar domain to a novel target system. For instance, in science, there is a range of examples of smart inventions and discoveries inspired in nature or other domains directly associated (Gentner & Smith, 2013): James Watt improved the design of the steam engine after observing a boiling tea kettle and George de Mestral invented Velcro mimicking the tiny crochet needles of the burrs that clung to his dog's fur. Marc Brunel found the inspiration for his work on tunnels underneath a navigable river borrowed from a worm, and Arthur

Fry created the Post-it notes by applying an adhesive accidentally developed to small pieces of papers. Nevertheless, in daily situations, people encounter serious difficulties to make effective use of potentially relevant prior knowledge.

These problem-solving situations certainly require access to prior knowledge to serve as a raw material for potential solutions. Nevertheless, although there is little doubt of the interplay of memory and reasoning, they have been traditionally examined as separate components. How people are able to access and use relevant knowledge is a central issue in human cognition. Given that, new ideas or searching for solutions is not a matter of mere chance, but the result of effective access and recombining prior stored knowledge, reasoning processes involving analogical transfer of knowledge or unusual remote associations may be influenced by the peculiarity of memory processes and explain failures in accessing relevant knowledge during analogical reasoning.

The purpose of this dissertation was to further expand our knowledge of the memory dynamics involved in analogical reasoning. More specifically, we aimed to investigate whether active memory control processes have the potential to influence subsequent analogical reasoning. In order to better understand this question, in the first introductory chapter of this work, we begin by examining the literature on memory accessibility and its underlying processes. We also review the

literature concerning analogical reasoning and summarize its principal findings. The introduction concludes with a description of the aims and organization of this work. In the experimental section, we describe the methods and main results of each of the four studies included in the dissertation. Finally, the main findings and their relevance for memory control and analogical reasoning are discussed and future directions for research are suggested.

PART I

Introduction

CHAPTER I:

Memory accessibility

Associative memory networks during problem solving

Memory plays a fundamental role in everyday reasoning situations by providing access to experiences that worked in the past or connect concepts that previously seemed to be remotely unrelated. Hence, the role of knowledge accessibility is crucial for idea generation and search for a suitable solution to a problem. The question is how are people able to form these rare remote associations and transfer what has been learned in one context to a novel one to solve a problem? Successful problem solving requires the solver's ability to access relevant knowledge at an appropriate moment and apply it to the problem-solving situation. Automatic access to knowledge is thought to be achieved through the spread of activation processes (Anderson & Spellman, 1995; Collins & Loftus, 1975; Ross, Ryan, & Tenpenny, 1989). According to associative memory theories such as the spreading activation model of Collins and

Loftus (1975), concepts are metaphorically represented in semantic memory as nodes, and relations between concepts are represented by the bi-directional links that interconnect these nodes. By accessing a concept, we refer to activating or bringing it into consciousness, which involves that activation spreads across the associative pathways to related nodes in the network (e.g. thinking about the *butter* would activate *bread*). In other words, whenever a person sees, hears or thinks about an idea, this information is activated in a person's memory, making their thoughts naturally go to associated words. For example, thinking about the word *jam* would bring to mind fruits like strawberries if one was recently talking about one's favorite breakfast or would activate the word *traffic* if one had rather been discussing about driving a car. Furthermore, this spread of activation would increase the likelihood of remembering these concepts during further cognitive tasks.

In this regard, research has provided evidence of how priming the availability of a concept makes it more likely to be used as relevant information in subsequent problem solving tasks (Day & Goldstone, 2011; Gick & Holyoak, 1980, 1983; Gómez-Ariza et al., 2017; Gross & Greene, 2007; Schunn & Dunbar, 1996). Schunn and Dunbar, (1996) provided evidence demonstrating that knowledge about a domain could enhance the performance of a reasoning problem from a different domain through implicit priming. They conducted an experiment in which, during an initial session, participants were first asked to solve a

biochemistry problem by discovering an inhibitory enzyme that decreased the reproduction of a virus population. In a second session, the same participants were asked to solve an unrelated molecular genetics problem whose solution involved inhibition of a set of genes. Results showed that participants that were previously exposed to inhibition concept during the initial session were more likely to propose the concept of inhibition to solve the molecular problem than control participants, even though participants reported not to be aware of the connection between the two problems. Other results further suggest that false memories may also prime creative problem solving as true memories do (Howe, Garner, Charlesworth, & Knott, 2011; Howe, Garner, Dewhurst, & Ball, 2010). In a series of experiments, the false memory priming assumption was explored by using Compound Remote Associate Tasks (CRAT) problems, which are meant to measure the creative ability of the participants to associate three given remotely associates items (e.g. COTTAGE-SWISS-CAKE and the participant has to come up with the solution, CHEESE). Critically, half of these problems had been previously primed by the presentation of Deese/Roediger-McDermott (DRM). This procedure typically involves the presentation of a list of associated words (bed, rest, awake, tired, dream, etc.) to a semantically related item non-presented in the context of the study (known as the critical lure; sleep). After a delay, when participants' memory is tested, the critical lure is often recalled or recognized as been

presented in the prior study list, indicating a false memory. In these experiments, the DRM's critical lures matched with the solutions to the problems. The results showed that, when the critical lure was falsely recalled, the corresponding CRAT problems were solved more frequently and faster than unprimed problems. The authors suggested that both the activation of false memories and priming of the problem solution may be explained by the same spreading of activation processes. During the DRM task, activation from concepts spread to other related concepts to the non-presented lure word. If the false memory remains activated during the later creative problem solving, CRAT solving may be facilitated by this prior activation. Altogether, these results provide evidence for the hypothesis that prior activation of knowledge may have the power to prime access to related information and promote problem solving.

The stronger the nodes are related semantically, the easier the amount of spreading activation flows, meaning that, activation would pass more strongly for closely related words than for more distant words (Collins & Loftus, 1975). For instance, in a word association task, if an individual is presented with the word *table*, he or she will likely respond *chair*, whereas a word such as *chemistry* would unlikely be produced. Thus, the manner in which people's semantic networks are organized may influence reasoning processes involving analogical transfer of knowledge or bringing together unassociated ideas to form unusual

combinations. In this regard, Mednick (1962), who defined creativity as the process of combining remote associations, proposed that the organization of the semantic network varies widely from individual to individual. According to his theory, a creative person would possess a richer and more flexible associative network, characterized by 'flat' or broader connections in which a stimulus activates both closely and remotely associated concepts that would facilitate an efficient search process. Similarly, differences between how experts and novices are able to access remotely associated concepts have been also suggested to depend on knowledge organization (Glaser & Bassok, 1989). Experts appear to have a more readily organization of knowledge characterized by a highly integrated network of clusters of concepts meaningfully connected with other elements, whereas novices' knowledge would be marked as a collection of isolated concepts not well-structured (Chi, Feltovich, & Glaser, 1981). Therefore, experts and creative individuals are better at retrieving and making connections to other information previously learned due to a tightly coupled and efficient organization of knowledge.

Nevertheless, there are situations in which people are not fortunate enough to possess an efficient associative memory organization and the solution to a particular problem involves ideas that are unassociated or weakly associated. In this context, retrieval of a

potential solution is in part determined by cognitive processes that modulate accessibility.

Memory accessibility and inhibition

Long-term memory has a seemingly unlimited capacity that allows us to store a wide range of information during our whole lifetime. Yet, in many situations in which we want to recall a specific memory, we simply cannot. Usually, the main constraint in recall is accessibility rather than availability: A memory representation that was readily accessible a few minutes ago, at some other time may be inaccessible. For example, in a situation in which a person is trying to recommend a restaurant to a friend, several locations of other restaurants where he or she previously had dinner may interfere, so impeding the recall of the intended restaurant's address. Although this inaccessibility does not mean that this memory representation has been forgotten in a permanent way, dealing with attempts to remember something can be very frustrating. The concept of accessibility is even more relevant in problem solving, given that only knowledge that is accessible at the appropriate moment will be actually used to produce a potential solution. Thus, how are people able to access and use relevant knowledge

at the appropriate moment? Memory accessibility is modulated by memory control processes that may either facilitate or hinder access to memory representations (Baddeley et al., 2015). In this context, inhibition has been proposed as a control mechanism that is thought to downregulate activation of irrelevant memory representations in order to facilitate access to relevant ones (Anderson, Bjork, & Bjork, 1994). Interestingly, as in the example described above, this suppression has been consistently shown to occur in interference situations wherein highly accessible but irrelevant information may disrupt the retrieval of a target memory (for a review see Storm et al., 2015). Given that the number of items to be retrieved and maintained in working memory at a particular moment is limited, inhibitory control processes allow for the retrieval of a target item at cost of reducing the likelihood that this related information will be retrieved in the future. So, the very act of retrieval of relevant information may decrease access to other related information (Anderson et al., 1994). For example, if somebody asks you what did you have for dinner last night, memories related to other dinners may interfere. The successful recall of the specific target memory (the meal we had last night), may be accomplished by inhibiting competing memories, so rendering interfering memories less likely to be accessed. Therefore, these mechanisms are thought to be recruited in order to temporally suppress competing information and prevent it from

achieving the awareness threshold, so that the target idea may be retrieved (Anderson, 2003; Anderson & Spellman, 1995).

Evidence of the role of inhibition as a control mechanism during memory retrieval has been studied using the Retrieval Practice procedure through the phenomenon of retrieval-induced forgetting (Anderson et al., 1994). This paradigm typically involves three phases: study, retrieval practice, and memory testing. During the first phase, participants are presented with pairs of category-exemplars items (e.g. FRUIT-Apple, FRUIT-Banana, ANIMAL-Monkey) to study. Then, in the second phase, participants are asked repeated times to practice retrieval of half of the exemplars from half of the categories by a given cue (e.g. FRUIT-Ap__) that appropriately complete the stem. Thus, three different types of items can be distinguished: practiced items from practiced categories (e.g. Apple, hereafter Rp+ items), unpracticed competitors from practiced categories (e.g. Banana, hereafter Rp- items) and non-practiced items from non-practiced categories (e.g. Monkey, hereafter Nrp items). Finally, after a brief distractor task, participants' memory for all the studied items during the first phase is tested, typically via a category cued-recall task.

It is not a surprise that results typically show a recall increase for Rp+ items compared to Nrp items, which serve as a baseline from non-practiced categories. What is more interesting and important here is that

Rp- items tend to be significantly worse recalled than Nrp items. This empirical effect, in which the selective retrieval of some information associated with a given category renders associated information less accessible, is referred as retrieval-induced forgetting (RIF; Anderson et al., 1994). According to inhibitory accounts of RIF, attempting to selectively retrieve target items of a category cue may cause the inappropriate activation of other associates. In order to override this competition, inhibitory mechanisms are thought to be triggered to reduce the accessibility of interfering associates, impairing later recall in a subsequent memory test (Anderson & Spellman, 1995). The retrieval-induced forgetting effect is robust and has been replicated many times using different materials and in a variety of setting such as eyewitness memory (Garcia-Bajos, Migueles, & Anderson, 2009), autobiographical memory (Barnier, Hung, & Conway, 2004), social cognition (Dunn & Spellman, 2003; Storm, Bjork, & Bjork, 2005), language selection (Levy, McVeigh, Marful, & Anderson, 2007), visuospatial stimuli (Ciranni & Shimamura, 1999; Gómez-Ariza, Fernandez, & Bajo, 2012) or lexical categories (Bajo, Gómez-Ariza, Fernandez, & Marful, 2006), and in this thesis, we want to explore whether reduced accessibility as a consequence of previous selective retrieval would also influence analogical problem solving.

Although some alternative theories have been proposed to account the RIF effect (Jonker, Seli, & MacLeod, 2013; Raaijmakers &

Jakab, 2013), a number of behavioral (Bajo et al., 2006; Levy & Anderson, 2002; Román, Soriano, Gómez-Ariza, & Bajo, 2009; Veling & van Knippenberg, 2004; Weller, Anderson, Gómez-Ariza, & Bajo, 2013), electrophysiological (Ferreira, Maraver, Hanslmayr, & Bajo, 2019; Hanslmayr, Staudigl, Aslan, & Bäuml, 2010; Johansson, Aslan, Bäuml, Gäbel, & Mecklinger, 2007; Spitzer, Hanslmayr, Opitz, & Mecklinger, 2009; Staudigl, Hanslmayr, & Bauml, 2010), neuroimaging (Kuhl, Dudukovic, Kahn, & Wagner, 2007; Wimber, Alink, Charest, Kriegeskorte, & Anderson, 2015; Wimber et al., 2008; Wimber, Rutschmann, Greenlee, & Bäuml, 2009) and stimulation studies (Penolazzi, Stramaccia, Braga, Mondini, & Galfano, 2014; Stramaccia, Penolazzi, Altoè, & Galfano, 2017) are consistent with inhibitory explanations of this effect. Importantly, these studies have shown that RIF is reliant on prefrontal control regions that are engaged in order to suppress competing items during retrieval practice (Anderson, 2003; Storm & Levy, 2012).

Recording electrophysiological measures of brain activity (EEG), Johansson et al. (2007) compared the brain activity elicited during a retrieval-practice and a relearning baseline condition. Whereas retrieval practice should engage competition and induce forgetting of the non-practiced material, relearning would serve as an appropriate baseline, given that selective retrieval does not occur while reprocessing the material and inhibitory control should not be triggered. Results showed

that the retrieval-practice condition evoked stronger positivity over frontal electrodes relative to the relearning condition. This stronger positivity predicted individual differences in the size of the subsequent RIF effect. The positive-going difference was greater in a high-forgetting group relative to a low-forgetting group. Similarly, Wimber et al. (2009) compared a retrieval practice with a relearning condition and showed that only selective retrieval led to the activation of the dorsolateral prefrontal cortex (DLPFC). Furthermore, the increased activity in the anterior cingulate cortex (ACC) and the DLPFC correlated with later forgetting. Consistently with these findings, an fMRI study by (Kuhl et al., 2007) showed dynamic reductions of the BOLD signal in the prefrontal cortex across repeated selective retrieval. Importantly, activity in the ACC and the right anterior ventrolateral prefrontal cortex (VLPFC) predicted subsequent forgetting. The activation of the right DLPFC covaried with changes in the ACC activation and correlated with the strengthening and facilitation of target memories. Regression analyses revealed that this prefrontal disengagement predicted the extent to which competing memories were forgotten. The decreased activity in these prefrontal areas suggests that successful forgetting is accompanied by reduced demands on cognitive control with repeated selective retrieval and is consistent with the role that the ACC would play in detecting and the DLPFC and VLPFC in resolving mnemonic competition. In a more recent study, Hellerstedt and Johansson (2014)

further studied the electrophysiological correlates of reactivation of competing memories and their role in retrieval-induced forgetting. To this end, the competition level during retrieval practice was manipulated by modifying the associative strength between category cue and competitors. Competitor activation was associated with an FN400 ERP effect over anterior and frontal electrodes. The authors interpreted this effect as evidence of the reactivation of associates to the category cue, consistent with prior research for the role of this component in conceptual priming and old/new familiar effects. Critically, the magnitude of this effect predicted greater forgetting for those competitors when probed on a later test, which is suggestive of the forgetting dependence on competitor activation. In this line, other electrophysiological studies have also linked oscillatory reductions in the mid-frontal theta band (~4-8 Hz) across retrieval practice trials with successful down-regulation of interference (Ferreira, Marful, Staudigl, Bajo, & Hanslmayr, 2014; Hanslmayr et al., 2010; Staudigl et al., 2010). Finally, evidence of the effects of inhibitory processes over memory representations has also been provided by another recent fMRI study by Wimber et al. (2015) in which they developed a tracking procedure to isolate and quantify the neural activation state of individual memories traces. The results revealed that repeated retrieval of target items progressively and selectively suppressed Rp- cortical traces that remained below baseline items activity. This pattern of suppression was

associated with the engagement of the VLPFC which, importantly, predicted later forgetting.

Altogether, the evidence from several fMRI and EEG studies suggests the engagement of prefrontal regions to exert inhibitory control during selective retrieval when interfering memories compete, which induces reduced accessibility (RIF) to these inhibited memories when trying to recall them in the subsequent memory test. These findings are consistent with the idea that the ACC may be involved in conflict detection (Ferreira et al., 2019; Staudigl et al., 2010), whereas the recruitment of other regions such as the right DLPFC and VLPFC that would reflect the implementation of inhibition over competing memory traces (Kuhl et al., 2007; Wimber et al., 2008, 2009, 2015).

While most of the research on the neural substrates of RIF has focused on brain activity during retrieval practice, a few studies have evaluated the substrates of this impairment during the final memory test (Kuhl, Kahn, Dudukovic, & Wagner, 2008; Spitzer et al., 2009; Wimber et al., 2008). Retrieval of Rp- items (those thought to be the target of inhibitory control) has been shown to increase activation over the left anterior region of the VLPFC (Wimber et al., 2008; but see Kuhl et al., 2008, who identified different PFC areas). The activity of this region has been previously linked to the retrieval of weak memory representations (Badre & Wagner, 2007). Therefore, the activation of this area could

reflect the weakened state of Rp- representations, as predicted by the inhibitory account. Accordingly, Spitzer et al. (2009) examined the electrophysiological correlates of RIF with a recognition test and found that the activity elicited by the recognition of Rp- items were characterized by reduced power in the theta (4–7 Hz) and gamma (60–90 Hz) bands. In addition, ERP results showed that the recognition of Rp- items were further accompanied by a reduction in amplitudes of the P2 ERP component compared to the recognition of Rp+ items. Frontal old/new effects in the P2 time window have been associated with modality-specific implicit priming so that these reduced amplitudes might reflect weak memory signals, which is in line with the idea that these memory traces were previously inhibited. By contrast, recognition of Rp+ items evoked a stronger late parietal positive (LPP) component. Previous research has associated the LPP component with old/new effects and episodic recollection of spatio/temporal information. Hence, the observed positivity of the LPP component might reflect the recollection of previously strengthened Rp+ items. The detrimental and beneficial effects of retrieval practice were dissociable and probably modulated by different processes.

Taken together, the findings of previous studies show reduced memory strength signals for competitor items at test, which again is in line with the idea that competing items are suppressed during retrieval

practice to promote retrieval of the appropriate memory target and support the inhibition account.

The consequences of the operation of memory control processes on memory accessibility may have significant implications in higher-level cognitive tasks such as reasoning. In this regard, recent studies have revealed that memory control processes may have the power to influence creativity problem solving (Gómez-Ariza et al., 2017) as well as biasing decisions (Iglesias-Parro & Gómez-Ariza, 2006) affecting access to potential solutions or alternatives. In the present work, we aimed to explore whether similar results regarding how a recall impairment of relevant information may impact greater complex reasoning tasks that go further word associations, such as analogical reasoning problem solving. In the following section, we now describe and review previous literature on this kind of inductive reasoning.

CHAPTER II:

Analogical reasoning

Defining analogical reasoning

Analogical reasoning is the ability to make inferences on the basis of resemblance or correspondence between two objects, situations, concepts or the like (Gentner, 1983; Hummel & Holyoak, 1997, 2003). Reasoning by analogy has been considered 'the core of human cognition' since it plays a significant role in problem solving, decision making, learning and communication (Gentner & Smith, 2013). In problem solving contexts, such as science, analogies can be used to find potential solutions by following the logic that if something worked in a given situation, it might also work in another situation in a similar way. In other contexts, an analogy can be used as a tool to understand new information by simplifying complex concepts. For instance, proverbs are interesting analogy examples that people use routinely in colloquial language based on purely perceived similarity matches. In a casual conversation, you may use idioms such as a 'like a fish out of water', expecting people to apply the relational pattern 'to feel awkward because

you are in a context for which you do not feel not suited. This kind of relational mapping is considered to be the core process in analogy (Gentner & Smith, 2013).

During analogical reasoning, a familiar domain, which is referred to as the analog or source, serves as a model by which one can comprehend and draw inferences about an unfamiliar domain, which is called the target. For example, during a sciences class, a teacher can explain the functional processes that take place in a cell (the target) by drawing an analogy with a factory (the source) (i.e. the mitochondrion may share similarities with the powerhouse of the cell, the ATP with the electricity or the Golgi apparatus with the warehouse) (Herr, 2008). This example illustrates how analogies involve identifying correspondences between two apparently unrelated topics and can be used to get a better understanding of a less well-known topic by relating back to prior knowledge driven by these commonalities.

Traditionally, laboratory research has focused on two types of problems to explore the people's ability to reason analogically. On the one hand, four-term classical analogies framed in the A:B::C:D logical format, which is read 'A is to B as C is to D' (i.e. DUCK is to FEATHERS as RABBIT is to ?), have been typically employed. These problems are frequently included in standardized tests such as the Miller Analogies Test (MAT) or the Scholastic Aptitude Test (SAT) (Meagher, 2006;

Schalkwyk, 2011). In this type of analogies, A, B and C terms are provided whereas solvers must generate the D term (or select it from several options). In other words, to generate a correct solution (D) to an A:B::C:D analogy, the reasoner must identify the relationship between the A and B solution so that the C:D relation somehow resembles the former (i.e. BIRD is to NEST as DOG is to ?, the correct solution would be KENNEL). Most research on this type of analogies has explored the relevance of semantic relations by using both word-based (Kmiecik, Brisson, & Morrison, 2019; Luo et al., 2003; Wendelken, Nakhabenko, Donohue, Carter, & Bunge, 2008) or pictured-base analogies (Cho, Holyoak, & Cannon, 2007; Krawczyk, Mcclelland, Donovan, Tillman, & Maguire, 2010; Krawczyk et al., 2008), although many studies have also tapped spatial relations by employing Raven's progressive matrices (Raven, 2003). On the other hand, another type of tasks, such as problem analogies, have been used to evaluate people's ability to reason in problem-solving contexts (Day & Gentner, 2007; Day & Goldstone, 2011; Gick & Holyoak, 1980, 1983; Schunn & Dunbar, 1996). Participants are typically presented with paragraph-length problems that have been already solved as a guide and, immediately or after a delay, a new problem is presented where an analogous solution is required (i.e. a biochemistry problem in which viruses were dormant as a consequence of inhibitory process and an analogous problem in the domain of molecular genetics whose solution required the inhibiting a set of genes;

Schunn & Dunbar, (1996). Finally, participants are tested on their ability to perceive relational similarity between both problems and to transfer and develop the appropriate solution to the current problem. Overall, both types of analogy problems provide the analog cues explicitly and attempt to measure the participant's skills to transfer knowledge.

Although a number of theories and computational models have attempted to functionally divide the processes of analogical processing, the nature of these may vary depending on the type of analogy (i.e., analogies in which the source is already presented or analogies that require access to the source). However, it is generally assumed that relational reasoning involves two major phases: mapping and retrieval (Hummel & Holyoak, 1997, 2003; Keane, Ledgeway, & Duff, 1994; Kokinov & Petrov, 2000; Sternberg, 1977). According to these accounts, analogical reasoning involves accessing and selecting a source analog in long-term memory given a current topic in working memory (mapping). Memory retrieval implies active search for a memory representation among a number of possibilities available that shares a similar set of characteristics to the current problem, and select the one appropriate for the problem (Gentner, Rattermann, & Forbus, 1993; Gick & Holyoak, 1980; Ross et al., 1989). The mapping phase is considered the essence of analogical reasoning (Gentner & Smith, 2013). Whereas some authors have proposed that mapping occurs when problems share a semantic similarity, structural consistency and goals (Holyoak, 1985; Holyoak &

Thagard, 1989), others have argued that subjects map over high-order relational structures, rather than projecting local matches (Gentner, 1983, 1989). Despite these differences, theories agree that during mapping, the source analog is aligned with the target by finding a resemblance between both representations and then projecting these inferences from one analog to the other.

The neural basis of analogical reasoning

It is not surprising that reasoning by analogy recruits a broad interconnected network of brain regions, especially the ones that are involved in cognitive control and semantic retrieval. Studies using functional magnetic resonance imaging (fMRI) have provided converging evidence of the crucial role that the (left) rostrolateral prefrontal cortex (RLPFC) plays during mapping, the process whereby simultaneously relations between concepts need to be compared and integrated, in nonverbal and verbal reasoning tasks (Bunge, Wendelken, Badre, & Wagner, 2005; Christoff et al., 2001; Green, Fugelsang, & Dunbar, 2006; Kroger, 2002; Prabhakaran, Smith, Desmond, Glover, & Gabrieli, 1997; Ramnani & Owen, 2004). For example, Bunge et al. (2005) presented a semantically related pair of words to their

participants, followed by an instructional cue indicating whether they had to perform an analogy or a semantic evaluation task, and then the second pair of words to which they had to respond. In the analogy condition, participants evaluated whether both pairs of words were semantically analogous, whereas in the semantic condition they had to determine whether the pairs were semantically related. In addition, the associative strength between the first pair of words was manipulated in order to disentangle the semantic-relatedness effects from the analogical reasoning effects. The results revealed that left RLPFC was recruited in analogy trials but not on semantic trials and that this region was insensitive to associative strength. The authors concluded that these results are consistent with the role of the left RLPFC in integrating the products of semantic retrieval to evaluate whether distinct representations are analogous. In contrast, the left ventrolateral prefrontal cortex (VLPFC) was sensitive to the associative strength of the words showing more activation for pairs with weaker semantic relations, which is in line with neural models postulating the involvement of this area in controlled semantic retrieval of weak memories (Badre & Wagner, 2007; Wimber et al., 2008). Similarly, Green, Fugelsang, Kraemer, Shamosh, and Dunbar (2006) reported enhanced activation of the left RLPFC cortex associated with judgments of analogous word pairs that required integration of abstractly similar relations. In this line, visuospatial reasoning studies have observed similar results by

employing matrix problem tests such as the Raven's Progressive Matrices (RPM). In this task, study participants receive a matrix of figures in which one is missing and they have to select among several alternatives the stimulus that matches the most (Raven, 2003). Because joint integration of multiple relations is required to infer the solution, this task is widely thought to involve relational integration and entail cognitive processes that are similar to those involved in four-term analogies (Krawczyk, 2012). In fact, several studies have revealed increased activity in the RLPFC when participants have to integrate two relational patterns of spatial relations when solving problems in the RPM test (Christoff et al., 2001; Crone et al., 2009; Kroger, 2002). Therefore, results from both visuospatial and verbal domains show that left RLPFC plays an essential role in the integration of multiple relations that is of service to analogical reasoning.

The dorsolateral prefrontal cortex (DLPFC) has shown to be sensitive to processes influencing the difficulty of the task, such as the level of interference from competing responses when the number of distractors is increased (Kroger, 2002). In this line, Bunge et al. (2005) found that activity in the right DLPFC was significantly greater when participants were to reject invalid analogies at the stage of semantic retrieval and integration. The authors concluded that this area might be involved in response selection during retrieval. In another fMRI study, Cho et al. (2010) employed a different paradigm to dissociate

interference resolution and relational integration components during non-verbal analogical reasoning. They found that a cluster in the right lateral PFC was sensitive to the need to dismiss distracting information, whereas the left RLPFC was specifically sensitive to relational integration demands. Therefore, whereas the RLPFC recruitment is consistent with an essential role in the integration of multiple relations, the DLPFC recruitment might support analogical reasoning by contributing to interference control and selection during retrieval.

Since electroencephalography measures add temporal specificity, recent event-related potentials (ERPs) studies have begun to investigate the time course of cognitive processing occurring at different stages of analogical reasoning. Most of these studies have specifically studied ERPs that underlie (1) the stage of schema induction and retrieval of the source and target relations (A:B) and (2) the mapping process that involves the integration of the relations and the projection of the inferences to form analogies (C:D or C). For instance, Qiu, Li, Chen, and Zhang (2008) recorded EEG while their participants performed a three-letter string (e.g., abc:abd::ijk:?, followed by the conclusion ijl) comparison analogy task in which participants were prompted to decide whether the target pair was correct according to the relationship in the source pair. They found that the schema induction stage (A:B) elicited more negative ERP deflection (N500-1000) and a more positive ERP component (P600-1000) which may be associated with the retrieval and integration of

alphabetical information in schema abstraction. In the stage of analogy mapping, more negative-going waveforms (N400-600) and a late negative component (LNC) were found over fronto-central areas, which may reflect activation of the schema, mapping to the target and maintenance of the products in WM. Importantly, dipole source analysis localized the generator of this late component in the left PFC. Similar results were obtained by Maguire, McClelland, Donovan, Tillman, and Krawczyk (2012), who compared ERPs of a semantic analogy task with those elicited by semantic and perceptual conditions lacking relational comparisons. During the encoding phase, the analogy condition, relative to the semantic condition, evoked significantly positive-going waveforms in left frontal electrodes starting at 500 ms after the stimulus presentation. During the mapping phase, similar spatial-temporal differences at 400-600 ms post-stimulus presentation were yielded by left-frontal electrodes for analogies compared to perceptual items. Consistently, Zhao et al. (2011) found that analogies elicited greater N400 components in both the schema induction and analogy mapping stages, possibly reflecting the presence of semantic retrieval and analogical transfer. Furthermore, the response production stage elicited a P2 component that may be associated with the identification and evaluation of the stimulus. These findings suggest that the encoding and mapping processes appear to be well differentiated eliciting different components.

Factors that influence analogical retrieval

Despite the fact that people use this type of inductive reasoning in a wide range of contexts and on a daily basis, research has demonstrated that they often fail to transfer relevant knowledge to new situations spontaneously (Gentner et al., 1993; Gick & Holyoak, 1980, 1983). In order to study the entire process of analogical thinking, Gick and Holyoak (1980;1983) introduced a procedure under which participants would solve a problem after providing them with a source analog in an incidental context. Firstly, participants were presented relevant information about the solution to a problem and then, at a later time, participants were asked to solve some current problem that was, in fact, analogous to the previous read one. They used the Duncker's radiation problem (1945) in which a doctor must destroy an inoperable malignant tumor. The doctor can use high-intensity rays that would destroy the tumor but also the healthy tissue they have to pass through. At a lower intensity, rays would not harm the healthy tissue but would be ineffective in destroying the tumor. The correct solution would involve projecting multiple low-intensity rays by targeting the tumor from several points around it. When participants were tested on their

ability to spontaneously solve the Duncker's radiation problem, only about 10% of participants managed to generate a convergence solution to it. In another condition, participants first read an analogous military problem story. In it, a fortress was attacked by a general who decided to break up the army into smaller groups so that each of the soldiers could pass over safety to avoid mines to blow up. Eventually, each of the small detachments of soldiers overthrew the fortress dictator by arriving along different roads. After reading this story, participants attempted to solve the radiation problem without a prior hint to use the army's story. Results showed that reading the analogous story led 30% of the participants to provide the correct solution. However, when these same participants were given a hint indicating that the story might be helpful for solving the radiation problem, the percentage of generated solutions increased to 80%. These results show that even when relevant knowledge was in long-term memory, it was not accessed when needed. Therefore, the results reported by Gick & Holyoak (1980; 1983) can be interpreted as suggesting that solvers may have difficulties in spontaneously recognizing the relevance of previous situations to solve a current problem appropriately. These findings have been replicated in a number of studies (Gentner et al., 1993; Holyoak & Koh, 1987; Ross et al., 1989).

Over the last forty years, research has addressed issues that affect appropriate transfer during analogical problem solving with most of the studies dealing with one of two main topics; namely, identification of

variables that might improve analogical mapping or transfer between source and target analogs, and nature of the retrieval process involved in these problem-solving situations.

The first approach has considered factors (i.e., surface or structural similarity, expertise, the role of the presentation of hints or cues) that would promote analogical reasoning. One of these factors that have shown to influence analogical mapping is the level of source-target similarity. In general terms, research has demonstrated that analogical retrieval is facilitated by surface similarities or easily accessible superficial features, whereas mapping is considered to be mostly driven by structural similarities involving higher-order relations (Gentner et al., 1993; Gick & Holyoak, 1980, 1983). A number of laboratory studies indicate that retrieval of a source analog is harder if there is no superficial similarity with the target problem, and it is facilitated by surface-based more than by structural similarities (Catrambone, 2002; Gick & Holyoak, 1980, 1983; Holyoak & Thagard, 1995; Keane, 1987; Reed, Vosniadou, & Ortony, 1991; Ross et al., 1989). However, naturalistic studies have demonstrated that people tend to rely on deeper structural relations to obtain distant retrieval of analogs (Blanchette & Dunbar, 2000; Máximo Trench & Minervino, 2015). Some authors have proposed that even though superficial analogies are easy to recognize or create, the transfer of structural relations between the source and the target would not be

guaranteed. By contrast, structural analogies might strongly influence the quality of the solutions (Gentner, 1989).

With regard to the level of expertise in analogical retrieval, results have shown that high experience in a certain matter significantly increases the rate of spontaneous access and use of within-domain analogies (Dunbar & Blanchette, 2001; Kretz & Krawczyk, 2014; Novick, 1988; Novick & Holyoak, 1991). Accordingly, novices in a domain rely more on the surface features of the problems, often fail to recognize structurally similar examples and are considered to lack skills to benefit from explicit prompts to use analogies. By contrast, experts are more able to establish successful analogies based on both structural and surface similarities as well as to avoid interference by examples that are similar only on the surface (Novick, 1988). In this line, studies by Dunbar and Blanchette (2001) reported that more than half of analogies produced *in vivo* settings by experts in biology or politics were structural in nature (showing no surface similarity).

Another factor that might influence the search for an analogous solution is the manipulation of whether subjects are informed of previous knowledge application. As in the Gick and Holyoak's (1980; 1983) experiments described above, participants seem to benefit from explicit cues to increase transfer effects (Gick & Holyoak, 1980, 1983; Novick & Holyoak, 1991; Perfetto, Bransford, & Franks, 1983; Ross et al.,

1989). For example, Perfetto et al. (1983) showed that presenting participants sentences that essentially contained the solution prior to the presentation of the current problem did not increase the number of solutions generated. Participants recognized the relevance of the hints only when they were explicitly prompted by the relation between the sentences and the problems to be solved. Additional evidence indicates that analogical reasoning can also benefit from strong retrieval cues, such as comparative gestures and visible alignment between source and target problems (Richland & McDonough, 2010) or from the use of strategies like 'bridging' in order to connect solutions conceptually (Clement, 1998).

A different line of research has addressed the retrieval dynamics during problem solving at the very moment they are operating. Evidence from behavioral studies suggest that interference from salient but inappropriate information while retrieving relevant information may influence analogical reasoning (Cho et al., 2007; Krawczyk et al., 2008; Morrison et al., 2004; Richland, Morrison, & Holyoak, 2006; Viskontas, Morrison, Holyoak, Hummel, & Knowlton, 2004). Hence, interference control, the ability to regulate activated but goal-irrelevant information, would be a necessary mechanism to restrain the processing of misleading features of a source or a target. In a series of analogical reasoning tasks, Cho et al. (2007) explored the influence of this factor by simultaneously manipulating the number of relations to be integrated as well as the need

for interference resolution. Results showed worse performance when it was required to integrate multiple relations and interference resolution was to be engaged at the same time, which interpreted as evidence of shared resources for working memory and cognitive control during analogical reasoning. In a patient-based study, Krawczyk et al. (2008) examined the involvement of the PFC in controlling interference from distracting information. Thus, the compared analogical reasoning performance in patients with frontal-variant frontotemporal lobar degeneration (FTLD), patients with temporal-variant FTLD and healthy controls. When semantic and perceptual distractors were presented as a possible response choice, the performance of frontal-variant FTLD patients was less accurate than that one of temporal-variant FTLD patients, who, in turn, performed worse than healthy controls. This finding would suggest that the prefrontal cortex may contribute to controlling interference from distractors in analogy problems.

In conclusion, several factors have been shown to facilitate the solver's ability to spontaneously access prior knowledge at the appropriate time, presumably by directing the search process. Nevertheless, in most ordinary problem-solving situations, the source analogs are not presented in the same context neither the solver has the privilege of being informed about the concrete part of the information that might be relevant to solve the problem. Although the similarity in surface or structural features shared between prior knowledge and the

problem statement may also influence the accessibility of relevant information during analogical reasoning, it cannot be easily controlled. These observations suggest that other factors may also modulate the spontaneous transfer of information in ordinary analogical problem-solving situations.

CHAPTER III:

Objectives and outline of the experimental series

Analogical reasoning is a central aspect of human intelligence and cognition. In everyday life, people reason analogically, when they understand the DNA structure is similar to a spiral staircase or the distribution of the electrons in an atom is similar to a cloud, or when the Wright brothers invented the airplane by solving the problem of restoring balance by drawing a parallel to the wings of the birds. Analogical reasoning plays an important role in learning, scientific discovery, problem-solving, as well as in decision-making.

Nevertheless, people often fail to use prior knowledge to solve a current problem. Research into the failures to access relevant information during analogical reasoning has examined a number of factors such as prior exposure to relevant information (Gick & Holyoak, 1980, 1983), surface and structural dissimilarity between source and target (Blanchette & Dunbar, 2000; Trench & Minervino, 2015), or low level of expertise about the analog domain (Novick, 1988). Although this evidence has examined the conditions that may constrain affecting

analogical transfer, in the present thesis dissertation we aimed to further examine the interplay between memory and analogical reasoning from another perspective. In a complementary view, another possible explanation for transfer failures would consider memory control mechanisms as responsible for the difficulties evidenced in accessing relevant information on analogical problem-solving. In other words, given that the production of a potential solution to analogies is not a matter of mere chance, but a consequence of cognitive operations on available knowledge, only the solution that is accessible in a particular moment will be used during analogical reasoning. Thus, for example, the inhibitory mechanism underlying retrieval-induced forgetting might prevent potential solutions from being selected and retrieved if they turn out to be relevant later in another cognitive task, such as reasoning. Therefore, the general aim of the present work was to better understand whether memory control processes may be responsible for difficulties in accessing potential analogies.

The first experimental series (Experiments 1 and 2) aimed to determine whether reduced memory accessibility might disrupt analogical problem solving unwittingly. In particular, we were interested in examining whether information that was previously inhibited during selective retrieval might impact the production of potential solutions in an analogical reasoning task. In order to explore this issue, we adapted the retrieval practice paradigm by replacing the final memory test to a set

of analogical problems whose potential solutions matched with the previously studied words so that the accessibility of potential solutions for subsequent analogies was manipulated. We predicted impaired analogical performance as a consequence of the cost of selective retrieval on the access to disrupt analogical reasoning performance when the forgotten information was later required to be accessed during problem solving. In other words, we expected unpracticed words to be less generated as potential solutions to the analogies than control words. This experimental series has been published in *PLoS ONE* (Valle, Gómez-Ariza, & Bajo, 2019).

Given that electrophysiological measures are assumed to have an excellent temporal resolution, these techniques may allow us to explore the neural correlates of memory control processes while they are operating, and in doing so help to disentangle the neural processes related to mapping and selective retrieval during analogical reasoning. Therefore, in Experiment 3, we used a procedure similar to that of Experiment 1 and collected EEG data throughout the whole experiment for the purpose of broadening our understanding of retrieval dynamics and its detrimental effects in a subsequent analogical reasoning task by recording ERPs. At a behavioral level, we expected to replicate the retrieval-induced impairment effect on analogical reasoning. At a neural level, considering recent research attempting to clarify the inhibitory neural substrates of retrieval-induced forgetting (Hellerstedt &

Johansson, 2014; Johansson et al., 2007; Kuhl et al., 2007), we expected memory interference to be reflected in changes of the ERP amplitude during selective retrieval practice. In this sense, the repetition of the cues along cycles should elicit reduced amplitudes of the FN400 ERP component that might reflect neural correlates of successful interference resolution. These differences should correlate with the amount later retrieval-induced impairment in the following analogical reasoning task. With regard to the detrimental effects on analogical reasoning performance, if inhibitory processes downregulate competing items during retrieval practice, so becoming less accessible, such deactivation may be reflected by different patterns of ERP correlates. Given that inhibition was directed to specific memory representations and not to more abstract relational information, these differences may be observed after the presentation of the C target and during the response time window (related to the retrieval of solutions), without affecting integration or mapping processes. This approach would help us to elucidate the temporal dynamics of analogical reasoning and disentangle mapping from selective retrieval processes.

As reported earlier, previous neuroimaging work investigating memory cognitive control have suggested that prefrontal regions, such as the right DLPFC that is believed to be a part of an inhibitory control network, is involved in downregulating stimulus-induced activation of misleading information that competes for retrieval (Kuhl et al., 2007;

Wimber et al., 2009). Nevertheless, although these studies identified regions whose activity is associated with direct suppression of misleading information during retrieval, the correlational nature of such evidence makes it impossible to establish causal links between performance in a task, processes involved and brain region. Therefore, finally, in Experiment 3, we further explored the neural substrates underlying memory control and how they would impact subsequent analogical reasoning by employing transcranial direct current stimulation (tDCS) in order to temporally modulate cortical excitability. On the basis of previous brain imaging studies pointing to the role that the right DLPFC would play modulating memory retrieval (Kuhl et al., 2007; Wimber et al., 2009), active cathodal stimulation was delivered over this area. Following a similar procedure that the one used in Experiment 2, tDCS was administered over this area during the retrieval practice phase, in which inhibitory are thought to operate according to inhibitory accounts (Anderson, 2003). We predicted that, if the right DLPFC plays a causal role in the suppression of competing information underlying the modulation of retrieval-induced forgetting, stimulation over this region may alter or eliminate retrieval-induced impairment on analogical reasoning performance relative to control stimulation. Furthermore, given that previous fMRI studies have indicated that different processes of analogical thinking appear to differentially recruit rostrolateral versus dorsolateral prefrontal subregions of the prefrontal cortex, (Bunge et al.,

2005; Hobeika, Diard-Detoeuf, Garcin, Levy, & Volle, 2016), we aimed to provide further evidence that dissociates such processes. Given that dorsolateral areas have not been related to the integration of multiples relations and transfer, we did not expect active stimulation to modulate the mapping process during the analogical problem-solving task. This study has been submitted to *Neuropsychologia.*

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PART II

Experimental Section

CHAPTER IV:
Inhibitory control during selective retrieval may hinder subsequent analogical thinking

Experiments 1 and 2

Analogical reasoning is a complex cognitive activity that involves access and retrieval of pre-existing knowledge in order to find a suitable solution. Prior work has shown that analogical transfer and reasoning can be influenced by unconscious activation of relevant information. Based on this idea, we report two experiments that examine whether reduced access to relevant information in memory may further disrupt analogical reasoning unwittingly. In both experiments, we use an adaptation of the retrieval practice paradigm (Anderson, Bjork, & Bjork, 1994) to modulate memory accessibility of potential solutions to a subsequent set of analogy problems of the type 'A is to B as C is to ?'. Experiment 1 showed a retrieval-induced impairment in analogical problem solving. Experiment 2 replicated this finding and demonstrated that it cannot be due to the deliberative episodic retrieval of the solutions to the analogies. These findings, predictable from an inhibitory framework of memory control, provide a new focus for theories of analogical transfer and highlight the importance of unconscious memory processes that may modulate problem solving.

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Introduction

Memory plays a prominent role in our everyday reasoning activities by allowing us to access relevant past experiences, which could thus be applied to new situations (Kokinov & Petrov, 2000). In the context of problem solving, considerable attention has received the way in which we access, retrieve and use stored knowledge to solve new problems (Blanchette & Dunbar, 2000; Gentner, Loewenstein, Thompson, & Forbus, 2009; Gick & Holyoak, 1980, 1983; Spellman, Holyoak, & Morrison, 2001). Much of this research has focused on inductive reasoning processes such as analogical thinking, which involves generating novel connections and transferring information from a well-known domain to a new one on the basis of similarities and correspondences (Holyoak, 2012). Analogical reasoning is seen as a fundamental tool in a wide variety of problem-solving contexts such as scientific discovery (Schunn & Dunbar, 1996), mathematics (Novick, 1995; Novick & Holyoak, 1991) or creative problem solving (Green, Cohen, Kim, & Gray, 2012). In all these contexts, memory plays a central role since information from one domain has to be accessed and applied to a different one. For instance, 'the solar system' analogy has been used to explain the atomic structure (how a planet orbits the sun can be thought as analogous to the way in which an electron orbits an atomic nucleus), but this analogy only can be inferred if the person already

knows about and have access to the stored information regarding the structure of the solar system (Hummel & Holyoak, 1997). There is considerable support for the claim that memory accessibility is crucial in analogical thinking; namely, the relevant source idea and potential analogies must be accessed, selected and retrieved from all the related information stored in long-term memory in order to map them and generate new inferences (Hummel & Holyoak, 2003).

A growing body of literature has started to examine how memory accessibility may influence analogical reasoning (Anolli, Antonietti, Crisafulli, & Cantoia, 2001; Blanchette & Dunbar, 2000; Christensen & Schunn, 2005; Howe, Garner, Threadgold, & Ball, 2015; Howe, Threadgold, Norbury, Garner, & Ball, 2013). Since memory is a dynamic process, there are mechanisms that can either facilitate or hinder access to the information stored in long-term memory and, thus, have an indirect influence on the reasoning process. A key issue concerns the degree to which participants spontaneously access and use relevant information during analogical reasoning. Hence, in some experiments, participants are exposed to information that would be useful for a subsequent problem-solving task without being informed about the relevance of the provided information. Even though research has demonstrated that people often fail to take advantage of this information (Gentner, Rattermann, & Forbus, 1993; Gick & Holyoak, 1980, 1983), a number of studies have also found evidence of how prior activated

knowledge impact reasoning and problem solving (Day & Gentner, 2007; Day & Goldstone, 2011; Gross & Greene, 2007; Howe et al., 2015; Kokinov & Petrov, 2000; Schunn & Dunbar, 1996).

However, there is some controversy on whether the possible impact of previous knowledge can influence analogical reasoning in both explicit and implicit manners. For example, it has been argued that awareness of encoding and retrieval processes is required to flexible application of knowledge in successful analogical transfer (Cohen, Poldrack, & Eichenbaum, 1997; Reber, Knowlton, & Squire, 1996). In this line, some studies have used explicit cues to prompt participants to remember analogous previous problems as a way of increasing transfer effects (Gentner et al., 1993; Gick & Holyoak, 1980, 1983; Novick & Holyoak, 1991; Perfetto, Bransford, & Franks, 1983). Gick and Holyoak (1983), for example, had participants generate a solution to treat a tumor without using radiation that would destroy the surrounding tissue. In the control condition where no analogical source was presented, only a 10% of participants came up with the solution. When previously provided with a similar solution but applied in a different incidental context without any hint that they could use the solution to approach the target problem, about 30% of participants generated analogous solutions. Notably, when these participants were explicitly told that remembering the previous story might be helpful to produce a solution to the problem, the percentage of convergence solutions increased to 80%. These results

suggest that spontaneous access to potential useful analogies may be difficult even when they are available in memory, unless explicit cues are provided.

In contrast, recent studies have shown that analogical mapping may act without an explicit prompt and without awareness of how solutions become accessible (Day & Gentner, 2007; Day & Goldstone, 2011; Gross & Greene, 2007; Howe et al., 2015; Kokinov & Petrov, 2000; Schunn & Dunbar, 1996). For example, in Gross and Greene's (2007) study participants learned a control sequence of faces (A>B, B>C, where A>C is usually inferred) or a transverse pattern set (A>B, B>C and C>A). Then, they learned a partial set of new faces (X>Y and Y>Z) and were tested for transfer on the new pair (X?Z). The group that was exposed to the transverse pattern C>A adopted the transverse pattering relations and selected Z>X at a greater extent than the control group, which rarely chose that pattern. Importantly, analogical transfer occurred even though participants were not explicitly prompted to do so and in the absence of awareness. Moreover, unconscious analogical thinking has been observed in a variety of context such as problem solving (Day & Goldstone, 2011; Schunn & Dunbar, 1996), text comprehension (Day & Gentner, 2007), false memories (Howe et al., 2015) and in absence of deliberate analogical strategies (Gross & Greene, 2007). In problem-solving contexts, for example, Schunn and Dunbar (1996) showed that knowledge about a domain could enhance performance of a reasoning

problem from a different domain through implicit priming. In their experiment, participants were first asked to solve a biochemistry problem by discovering which viruses were in a dormant state as a consequence of an inhibitory process. In a second session, participants solved an unrelated molecular genetics problem whose solution involved inhibition of a set of genes. Both biochemistry and molecular genetics problems solutions involved the same concept of inhibition. The authors found that participants that were initially exposed to the biochemistry problem were more likely to propose the concept of inhibition to solve the second problem and solved it faster than control participants. Furthermore, participants reported not to be aware of the relationship of the solutions between the two tasks. Similarly, Day and Goldstone (2011) found evidence of analogical transfer of strategies between two unrelated tasks. Participants who first learned how to solve a concrete perceptual simulation of a physical system were better at solving a task with very dissimilar domain and appearance, which involved an analogous structure and strategy. In addition, the transfer was independent of the participants' explicit reports about their awareness of the application of the analogous strategy.

Other results suggest that false memories could also prime problem solving and reasoning tasks as true memories do. Howe, Garner, Threadgold and Ball (2015) primed solutions in analogical problem solving by exposing participants to Deese-Roediger-

McDermott (DRM) lists. In a standard DRM experiment, participants first study a list of words that are associates (e.g., tiger, circus, tamer, roar…) of a critical semantically related item (e.g., lion), which is never presented at the study. After a retention interval, the participants' memory for the studied words is tested. The usual result is that participants produce or endorse the critical lure as a previously studied word as a consequence of the semantic relatedness between studied words and critical lures. In Howe et al.'s (2015) study, after a free recall test, participants solved analogies of the type 'A is to B as C is to D' in which they had to generate the 'D' term (e.g., peace is to dove as courage is to ?). Some of the analogies' solutions were critical lures of the DRM lists (false memory primed solutions, e.g., lion), whereas the remaining solutions were neither included in the lists nor related to them (unprimed solutions). Results revealed that participants solved significantly more analogies whose solutions were primed by false memories (critical lures) than analogies whose solutions were not primed. When participants were questioned on whether they noticed the two tasks were related, most reported that they did not think that there was a connection between the two phases. Taken together, these results seem to suggest that prior activation of knowledge by an unrelated task may make relevant information more readily accessible for solving analogical problems. Thus, presenting certain pieces of information has

the potential to prime access to related information and implicitly enhance analogical thinking.

The question here, however, is whether situations that temporarily render relevant memories inaccessible might, in turn, hinder analogical problem solving. Given that the generation of potential solutions relies on access to memory, if potential solutions are made less accessible and harder to retrieve during problem solving, performance should be impaired. Hence, any process that reduces the accessibility of relevant information in memory might hamper analogical reasoning. A control mechanism that is thought to decrease activation of memory representations is inhibition, which would be in charge of downregulating irrelevant but competing memories to facilitate access to relevant ones (Anderson et al., 1994). The role of inhibitory control as a mechanism to overcome interference during episodic retrieval has been extensively studied with the retrieval practice (RP) procedure. In this procedure, participants engage in practicing retrieval of only some of the previously studied items. While this selective retrieval usually leads to better accessibility (enhanced recall/recognition) of practiced items, it also causes the temporary inaccessibility (worse recall/recognition as compared to control items) of related non-practiced items that compete for retrieval during practice. According to an inhibitory framework (i.e., Anderson, 2003; Anderson & Levy, 2009; Bäuml, 2007; Gómez-Ariza, Fernandez, & Bajo, 2012; Weller, Anderson, Gómez-Ariza, & Bajo,

2013), this retrieval-induced forgetting (RIF) phenomenon is the aftereffect of inhibitory control exerted during selective retrieval, so that competing information that was previously inhibited remains in a below-baseline activation state that renders it less accessible if, later, this information becomes relevant and has to be retrieved. While most research on RIF has been conducted by using recall and recognition tasks to look into the consequences of inhibitory control (for reviews, see Murayama, Miyatsu, Buchli, & Storm, 2014; Storm & Levy, 2012), the retrieval practice (RP) procedure has also proved to be an useful tool to study the influence of memory activation and inhibition on thinking and decision making.

For example, Iglesias-Parro and Gómez-Ariza (2006) found that participants' judgments about the suitability of imaginary prospective candidates for employment could be biased by means of reduced access to relevant information. In their study, they used an adapted version of the retrieval practice paradigm (Anderson et al., 1994) so that participants were first presented candidates for a telephone insurance seller job position who were described with relevant (i.e. nice voice or verbal fluency) and irrelevant (i.e. tall or single) attributes. Then, participants practiced retrieval of irrelevant attributes related to one of the candidates. Lastly, participants were asked to choose the best candidate for the job position before a final memory test. As expected, participants selected the candidate whose irrelevant attributes were not

selectively retrieved, so showing selective forgetting of the competing applicant's relevant attributes. Hence, making a decision in the context of a personnel selection task was biased by means of the retrieval-induced inhibition of job applicants' traits. Consistent with this finding, one recent study also demonstrated that creative thinking might be adversely affected by reduced accessibility to relevant information (Gómez-Ariza et al., 2017).

Taken together, these findings suggest that reduced access to relevant representations in memory would result in poor performance in any problem-solving task as long as it strongly relies on memory accessibility. With the aim of putting to an empirical test this idea, the present experiments focus on analogical reasoning. The idea is that if potential solutions become less accessible from memory as an aftereffect of selective retrieval (i.e., via inhibitory control), subsequent performance on analogical problems should be impaired. Of special relevance here, given the controversy regarding whether modulating accessibility of previous knowledge can implicitly influence analogical reasoning (Cohen et al., 1997; Reber et al., 1996), we designed the present experiments so that if any, the possible negative effect of selective retrieval on analogical reasoning did not rely on explicit retrieval of previously presented information. Thus, we did our best to avoid that participants noticed the connection between the retrieval practice and the problem solving phases.

Experiment 1

Experiment 1 aimed to determine whether memory accessibility might unconsciously impact analogical problem solving. Specifically, we were interested in exploring whether items that had previously been the target of inhibitory control during selective retrieval were less likely to be chosen as solutions in an analogical reasoning task. To this end, the RP paradigm (Anderson et al., 1994) was adapted to manipulate the accessibility of candidate words as solutions for subsequent analogy problems. In the standard RP paradigm, participants typically study a list of category-exemplar pairs (e.g., Fruit-Banana, Fruit-Melon, Furniture-Shelving, Furniture-Wardrobe). Then, they are asked to selectively retrieve half of the items of half of the categories by a given a cue (e.g., Fruit-Ba____). Finally, a recall (or recognition) test is administered for all the studied items. As previously mentioned, selective retrieval usually facilitates later recall of practiced (Banana) items compared to control items (unrelated and unpracticed; Shelving and Wardrobe). On the contrary, unpracticed related items (Melon) are worse recalled than control items, which may be understood as an aftereffect of inhibitory control that acted on these competing items in memory during the selective retrieval of practiced items (e.g., Anderson, 2003; Levy & Anderson, 2002; Storm & Levy, 2012).

With the idea of exploring if memory inhibition may also affect analogical thinking, in the present experiments we replaced the final memory test typically used in the RP procedure with a set of analogical problems whose solutions matched some of the studied words. The analogical problems consisted of four-term analogies of the type 'A is to B as C is to D' generally employed in standardized intelligence and vocabulary knowledge tests (Sternberg, 1977). In this type of analogies, the A, B, and C terms are presented and solvers must find the D term to complete the sentence. That is, the participant had to be able to connect the different terms by finding a relationship between the two first pair of concepts in order to map it to the third word and find a suitable solution (e.g., BIRD is to FEATHERS as DOG is to ?). We predicted that to the extent that selective retrieval leads to the inhibition of competing items in memory, if these competing items turn out to be potential solutions in a subsequent test of analogical reasoning the inhibited words should be less accessible and harder to produce as D terms of analogy problems. This expectation only follows if analogical reasoning makes use of previously activated/inhibited knowledge in an implicit manner.

Method

Participants

30 undergraduate students (mean age = 19.67 years; *SD* = 1.92) from the University of Granada participated in the experiment in exchange for course credit. This sample size was determined on the basis of the number of participants included in related previous studies that looked into the effects of selective retrieval on problem solving (e.g., Gómez-Ariza et al., 2017; Iglesias-Parro & Gómez-Ariza, 2006; Iglesias-Parro, Gómez-Ariza, & Arias, 2009). All participants were native Spanish speaker, had normal or corrected-to-normal vision and gave their written consent to participate in the experiment by signing the appropriate informed consent paperwork. The Ethics Committee of the University of Granada approved the procedure of this study.

Materials

We used the items employed by Bajo, Gómez-Ariza, Fernandez and Marful (2006; see also Gómez-Ariza et al., 2012, 2017) with some modifications and the addition of new categories and items. The material consisted of fifty-four Spanish words from nine different orthography-based categories. Two additional categories of two words each were created and used as fillers at the beginning and at the end of the study lists in order to control for primacy and recency effects. Each orthographic category was composed of six (semantically unrelated) words that shared their first two letters (e.g., Maquillaje, Marinero, Matanza, Madurez, Maleta and Manual for the category MA). All the

words were chosen according to their lexical frequency from the (Alameda & Cuetos, 1995) database. Each category was composed of three medium-high frequency words (range= 34-98, *M*= 58.78) and three medium-low frequency words (range= 10-36, *M*=20.15). Medium-low lexical frequency words were used as to-be-practiced (Rp+), unpracticed control (Nrp+) and unprimed (Up+) items depending on the across-participants counterbalance condition. Medium-high lexical frequency words were used as related unpracticed (competing) items (Rp-), unpracticed control (Nrp-) items, or unprimed words (Up-) also depending upon the counterbalance version. As in previous RIF studies, the idea was to have competitive enough (high-frequency) Rp- items to maximize the need of inhibitory control during the phase of selective retrieval of the (low-frequency) Rp+ items (Anderson, 2003; see also Bajo et al., 2006). Moreover, the words selected (a) did not share apparent semantic relationship among the words belonging to the same category (b) were between two and five syllable lengths and (c) had a unique third letter. Six counterbalanced versions of the study material were created and used across participants so that every category rotated and appeared in the practiced, unpracticed, and non-studied conditions. In each version, three categories were studied and practiced (i.e., BA, DE, MA) and produced Rp+ and Rp- items; three categories were studied but not practiced and produced Nrp+ and Nrp- control items (i.e., CA, PE, FA)

and the last three categories were unstudied and produced Up+ and Up- unprimed items (i.e., DI, RE, TA).

Fifty-four analogical reasoning problems of the logical type A : B :: C : D (A is to B as C is to ?) used in standardized tests were created (e.g., Miller Analogies Test (MAT) or Scholastic Aptitude Test (SAT); Meagher, 2006; Schalkwyk, 2011). Each problem could be solved with one of the fifty-four words from the nine categories described above (AVARICIA es a GENEROSIDAD como INFANTILISMO a... whose solution would be MADUREZ; GREED is to GENEROSITY as INFANTILISM is to…, for MATURITY). Most of the relationships between the pairs of terms (A to B and C to D) were based on synonymy, antonymy, part to whole, cause and effect, degree, exemplar- category and object-action relations. Analogy problems were constructed taking into account associative strengths (forward and backward associative strength < .20) according to Spanish free association norms (Fernandez, Díez, & Alonso, 2014; Fernandez, Díez, Alonso, & Beato, 2004). Analogies were chosen from a preliminary normative study in which 57 participants were asked to provide a solution to each problem. The study was conducted to ensure that the experimental items had an appropriate difficulty level. Hence, only those analogies with a success rate ranging from 20% to 80% were selected (for a similar criterion, see Howe et al., 2015). The mean percentage of correctly solved analogies was 44.73% (*SD* = 19.75). The nine categories were split into three different sets (BA-

DE-MA, CA-PE-FA and DI-RE-FA) to be used in each of the counterbalance conditions as practiced (Rp+ and Rp- items), control (Nrp+ and Nrp- items) or unstudied (Up+ and Up- items) categories. The sets were matched for difficulty level so that there were no reliable differences between them (Group BA-DE-MA mean accuracy = 41.90; Group CA-PE-FA mean accuracy = 48.34; Group DI- RE-TA mean accuracy = 45.02; $p > .05$).

Procedure

Participants were randomly assigned to one of the six counterbalanced conditions and were tested individually. They were told that they would participate in two different and separate experiments; one concerning memory and the other related to analogical thinking. Hence, there was not an explicit link between the studied words and the analogy problems. The experimental session went through three main phases: study, retrieval practice and analogical problems test.

Study phase

In this first phase, participants were asked to memorize, for an upcoming memory test, word pairs composed of a lexical category represented by the two first letters (syllable) of a set of words and a word that belonged to that category (e.g., BA-Balanza). They were told to pay special attention to the first syllable of the word that identified the

category to which the word belonged because this category would be used as a retrieval cue in the upcoming memory test. Each pair was presented in the center of the screen for 5 s with a 1 s inter-stimulus interval. Four pairs were used as fillers and appeared at the beginning and at the end of the list to reduce primacy and recency effects. Thirty-six experimental pairs (6 out of the 9 possible categories) plus the filler ones were presented twice with each pair in each list presented in random order.

Retrieval practice phase

In this phase, participants were asked to repeatedly recall words of the previous phase. In each trial, a fixation cross was presented followed by the category label (e.g., CA) for 2 s and then the first three letters of the target word (e.g., Car_____) for 6 s. Participants were asked to recall aloud the studied word which matched with the cue. Only half of the items from half of the studied categories were presented during selective retrieval, which makes a total of nine Rp+ items. They were presented in separate blocks of three words with a filler item at the beginning and the end of each block. The blocks were displayed five times in a pseudorandom order. At the end of this phase, participants completed a distractor task for 5 minutes (completion of basic arithmetical operations; e.g., 3 x 2 + 6).

Analogical thinking phase

At the end of the session, participants were instructed to solve analogy problems by finding the relationship between A and B, and by thinking of a word that was related to C in the same way. No reference was made to the previously studied materials and participants were engaged in this phase as part of a different experiment.

They were first given examples of how to solve analogy problems and then provided with two practice problems with solutions. Then, the analogical test started. On each trial, the analogy was presented in the center of the computer screen for a maximum of one minute. Participants were asked to come up with a solution aloud and press the space bar afterward. A total of 54 analogical problems were presented. 36 analogies related to the words studied in the first phase. Eighteen additional problems were not related to any of the studied words and were added as fillers that represented problems with unprimed solutions. Analogies were presented randomly in two separate blocks in order to control for output order effects. First, a block including problems whose possible solutions were related to unpracticed, unrelated unpracticed (control) and unstudied words (Rp-, Nrp- and Up-, respectively) was presented. Then, a block with problems for which the solution word corresponded with practiced, control and unstudied words (Rp+, Nrp+ and Up+) was presented. Each analogy was scored with either 1 (correct) or 0 (incorrect or unsolved) by using a two different scoring procedures: namely, a strict scoring criterion (the response to each analogy was

considered correct only if it exactly matched the target word on the study list) to minimize bias during scoring, and a lenient criterion (the response was considered correct as long as it was similar (i.e., a synonym) of the exact word they studied at the first phase).

Finally, participants were given a questionnaire to learn about the strategies they used during each phase (study, retrieval practice and analogical problem solving) and whether they were aware of the relationship between the memory task and the analogy problems. The entire experimental session lasted approximately one hour, depending on the participants' speed to solve the problems. Presentation of the items in the experiment was controlled by E-prime 2.0 (Schneider, Eschman, & Zuccolotto, 2002).

Results and discussion

The mean percentage of success during the retrieval practice phase was 61.11 (*SD* = 25.06) and the mean percentage of analogies that were correctly solved was 54.32% (*SD* = 10.09), which reflect a relatively good general performance on the tasks. Figure 1 shows mean percentages of correctly solved analogies and solution times for each type of item. Two separate repeated-measures analyses of variance (ANOVA) were

performed on the percentage of analogy problems correctly solved with studied items and on reaction times.

Retrieval-induced impairment effect. To assess the negative effect of retrieval practice on analogical problem solving we conducted an ANOVA with type of item (Rp-, Nrp- and Up-) as the factor and accuracy rates as the dependent variable. The analysis applying a strict scoring criteria showed a reliable effect of type of item $F(2, 58) = 5.118$, $MSE = 1444.44$, $p = .009$, $\eta_p^2 = .15$. Follow-up comparisons revealed that participants solved significantly fewer analogies with Rp- words ($M = 51.48$, $SD = 21.14$) than with Nrp- items [$M = 61.48$, $SD = 18.16$), $t(29) = -2.162$, $p = .039$, $d = 0.51$], indicating that unpracticed words that were related to practiced items were less generated as solutions than unpracticed control items. In addition, Nrp- items ($M = 61.48$, $SD = 18.16$) were reliably more generated as solutions than Up- items ($M = 48.15$, $SD = 18.30$), $t(29) = 3.19$, $p < .01$, $d = 0.73$, which reveals a priming effect in analogical problem solving. Finally, there was no reliable difference between Rp- ($M = 51.48$, $SD = 21.14$) and Up- items ($M = 48.15$, $SD = 18.30$) ($t(29) < 1$, $p = .43$, $d = 0.16$). Hence, the retrieval-induced impairment on studied but unpracticed items was comparable to the effect of not presenting these items for study.

The analysis performed when applying a lenient criterion to score the solutions revealed exactly the same pattern. Thus, there was a reliable

effect of type of item $F(2, 58) = 6.25$, $MSE = 1400.55$, $p = .003$, $\eta_p^2 = .177$. T-tests confirmed that analogies were still solved less frequently with Rp- items ($M = 58.15$, $SD = 20.57$) than with Nrp items ($M = 67.41$, $SD = 17.73$), $t(29) = -2.22$, $p = .034$, $d = 0.48$. In addition, Nrp- items ($M = 67.41$, $SD = 17.73$) were reliably more generated as solutions than Up- items ($M = 54.07$, $SD = 16.95$), $t(29) = 3.67$, $p = .001$, $d = 0.77$, and there was no reliable difference between Rp- ($M = 58.15$, $SD = 20.57$) and Up- items ($M = 54.07$, $SD = 16.95$), $t(29) = 1.076$, $p = .291$, $d = 0.22$.

A similar ANOVA on reaction times (in ms) when applying the strict scoring criteria failed to reveal differences between Rp- ($M = 7683.93$, $SD = 3932.69$), Nrp- ($M = 8332.64$, $SD = 3830.08$) and Up- items ($M = 8125.51$, $SD = 3871.46$), $F(2, 58) < 1$, $MSE = 3293621.58$, $p = .52$, $\eta_p^2 = .022$. We also failed to observe a reliable effect on reaction times when using a lenient scoring criteria [Rp-: $M = 8236.70$, $SD = 3530.74$; Nrp-:

M = 8413.03, *SD* = 4119.79; Up-: *M* = 8348.24, *SD* = 3796.31, *F*(2, 58) < 1, *MSE* =238635.65, *p* = .94, η_p^2 = .002].

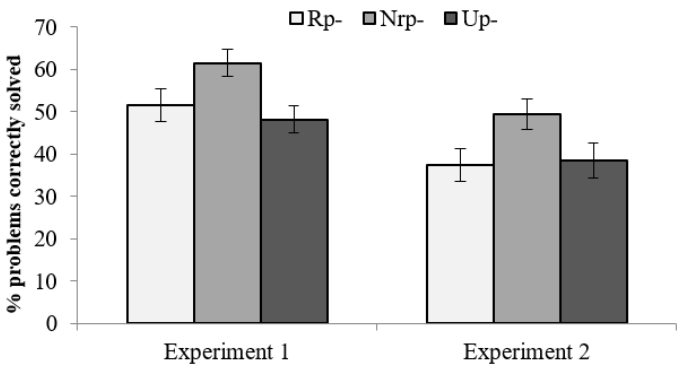

Fig 1. Performance on the analogical test as a function of the status of the solutions (error bars represent the standard error of the mean). Rp- = Solutions that were competitors during retrieval practice. Nrp- = Solutions that were not competitors during retrieval practice. Up- = Solutions that were neither competitors during retrieval practice nor previously studied.

Facilitation effect. To evaluate the possible benefit of retrieval practice on analogical thinking we conducted an ANOVA on accuracy with type of item (Rp+, Nrp+ and Up+ words) as the repeated-measure factor. The analysis using the strict scoring procedure revealed a reliable effect, *F*(2, 58) = 7.14, *MSE* = 2392.31, *p* < .01, η_p^2 = .198. Follow-up

analyses failed to reveal reliable differences between Rp+ (M = 63.33, SD = 20.03) and unpracticed (Nrp+) control items [M = 55.92, SD = 18.33), $t(29) = 1.55$, $p = .13$, $d = 0.39$] , even though there was a trend towards better performance for practiced items. We however found a facilitation (priming) effect that resulted from presenting the potential solutions during the first phase of the experiment since Nrp+ problems (those whose solutions were presented during study but belonged to unpracticed categories) were better solved (M = 55.93, SD = 18.33) than the Up+ problems (M = 45.56, SD = 15.54), whose solutions were never presented, $t(29) = 2.11$, $p = .04$, $d = 0.61$. In addition, participants significantly produced more Rp+ solutions (M = 63.33, SD = 20.03) than Up+ solutions (M = 45.56, SD = 15.54), $t(29) = 3.97$, $p < .01$, $d = 0.99$. The ANOVA on accuracy when using the lenient scoring procedure the effect of type of item did not reach significance, although it was close to it [$F(2, 58) = 2.83$, $MSE = 882.03$, $p = .07$, $\eta_p^2 = .089$; Rp+: M = 66.67, SD = 21.04; Nrp+: M = 62.59, SD = 15.02; Up+: M = 55.93, SD = 16.11].

The ANOVA performed on reaction times data failed to show a reliable effect of type of item either when using strict [Rp+: M = 7807.93, SD = 3736.11; Nrp+: M = 6486.90, SD = 2146.71; Up+; M = 7754.53, SD = 3446.54; $F(2, 58) = 2.86$, MSE =16774321.83, $p = .065$, $\eta_p^2 = .090$] or lenient scoring criteria [Rp+: M = 8027.45, SD = 3731.60; Nrp+: M = 6891.41, SD = 2319.15; Up-: M = 8113.68, SD = 3036.54, $F(2, 58) = 2.43$, MSE =13959872.96, $p = .10$, $\eta_p^2 = .077$].

In an attempt to better understand performance on the analogy task, we looked whether success at retrieval practice predicted either overall accuracy at test or impairment for Rp- items. Pearson correlation analyses failed to showed linear relationships both using the strict (r = .250, p = .183 and r = -.117, p = .537, respectively) and the lenient scoring procedures (r = .111, p = .560 and r = -.168, p = .376, respectively). This lack of relationship between retrieval practice success and final test accuracy is not surprising since literature on RIF has systematically shown this to be the case (Murayama et al., 2014; Veling & van Knippenberg, 2004). Finally, participants' responses to the questionnaire indicated that 23 out of the 30 participants (77%) became aware of the connection between the memory and the problem-solving tasks and recognized that they tried to solve the analogical problems by recalling the previously studied words. Critically, almost all these participants (73.33%) reported they were aware of such a relation at the end of the final test, when practiced (Rp+) items were presented and they noticed these words could be used as solutions. Hence, it seems reasonable to claim that, at least to some extent, performance during the first block of problems (whose potential solutions were unpracticed and unstudied items) was scarcely modulated by conscious retrieval of studied items. Although some studies have reported reliable RIF effects on response times using recognition memory tests (Veling & van Knippenberg, 2004), we did not observe any facilitation/inhibition effects on this

measure. Given that our analogy test would require a number of processes in addition to recognition (such as mapping and evaluation) response latencies might not be sensitive to the underlying memory control processes involved during analogical reasoning.

In summary, we found that items that competed for retrieval - and presumably were the target of inhibitory control during the practice phase- were selected to a lesser extent as solutions of the analogical problems than control items. This was so in the context of a separate problem-solving task that most participants failed to connect with the previous stages of the experimental session. Hence, this finding joins previous results to show that the cost of accessibility that follows selective retrieval may also be observed on tasks requiring more than only recalling specific episodic memories. Thus, in addition to the impact that memory inhibition has shown on decision making (Iglesias-Parro & Gómez-Ariza, 2006) and the resolution of creativity problems (Gómez-Ariza et al., 2017), the present results indicate that retrieval-induced forgetting may also hamper analogical reasoning.

An additional contribution of the present experiment is that it provides a complementary measure of the disruptive effect that memory inhibition may have on the accessibility to potential solutions on analogical problem solving. Specifically, here we were able to more precisely estimate the selective impairment for inhibited solutions by

including problems whose potential solutions were never presented in the context of the experiment. Hence, Up- solutions provide a baseline measure of the effect of the previous presentation (study) of the items that could become solutions. Given that the generation of Rp- solutions during analogical thinking was similar to that for Up- solutions, we interpret that inhibitory control during selective retrieval lowered the accessibility of competing memories so that participants behaved as if Rp- solutions had not been previously presented.

Experiment 2

The results of Experiment 1 indicated that reduced access to previously inhibited information influenced analogical problem solving by reducing the probability of coming up with a solution if it was previously inhibited during selective retrieval. In designing Experiment 1, we assumed that the access to targets to solve analogies might be implicit, since we made a serious effort through instructions to separate the memory and analogy tasks by making participants believe that these tasks were completely independent of each other. Despite this, most participants reported that they ended up being aware of the possibility of using the studied words to solve the problems. Hence, it could be the case that rather than testing whether inhibition of relevant information could implicitly affect performance on the analogical test, we were directly assessing episodic memory. That is, during problem solving participants

could have attempted to think back on the words previously studied in order to solve analogies without genuinely applying analogical mapping processes. This would especially be so for the Rp+ critical items, which were repeatedly presented during the practice phase of the experiment. Interestingly, in our procedure the analogies that could be solved with practiced (Rp+) and unpracticed (Rp- and Nrp-) items were presented in two different blocks. Thus, participants first attempted to solve Rp- and Nrp- analogies and then moved to the block with analogies whose solutions could be Rp+ and Nrp+ items. Therefore, those who reported awareness of the relationship between the two tasks at the half or the end of the problem-solving test might have noticed the connection while they were solving the second block of analogies. If so, they might have thought back only during the second testing block. In order to better determine to what extent participants implicitly accessed potential solutions to solve the analogies without explicitly using episodic retrieval, we conducted a second experiment where the procedure for the study and practice phases was identical to that used in Experiment 1, but the analogical test only included analogies that could be solved with Rp-, Nrp- and Up- items. Hence, participants were not given problems whose potential solutions were Rp+, Nrp+ and Up+ items. We expected this testing procedure to minimize the participants' awareness of the relationship between the memory and the reasoning stages of the experimental session. The new procedure would allow us to replicate the

main finding of Experiment 1 as well as to precise to what extent participants may deal with analogy problems without noticing the above-mentioned relationship.

Method

Participants

Based on the results obtained in Experiment 1, and before starting to conduct Experiment 2, we decided to have the same sample size in the present experiment. Thus, thirty undergraduate students (mean age = 19.87 years; *SD* = 1.45) from the University of Granada participated in the experiment for course credit. None of them had participated in the previous study. All participants were native Spanish speaker, had normal or corrected-to-normal vision and gave their written consent to participate in the experiment by signing the appropriate informed consent paperwork. The Ethics Committee of the University of Granada approved the procedure of this study.

Materials and procedure

The material and procedure were the same as in Experiment 1, except that in the final (problem solving) test participants only solved analogies whose solutions corresponded to Rp-, Nrp- and Up- items.

Results and discussion

Only 8 (27% of the) participants reported being aware of the relation between the memory and the analogy tasks, which indicates that the present procedure was successful (in comparison to that of Experiment 1; two samples proportion test with $p < 0.01$) at enhancing the implicit nature of the analogical test. These eight participants exhibited a totally different pattern of performance on the problem-solving test in comparison to the remaining participants. Specifically, they produced more Rp- ($M = 73.61$, $SD = 10.18$) than Nrp- solutions ($M = 59.72$, $SD = 10.18$) to the problems, even though a Wilcoxon test failed to reveal a reliable effect. Hence, eliminating problems related to Rp+ items from the analogical test drastically reduced awareness of the relation between the different stages of the experiment. Since we wanted to assure that the results were not due to explicit memory strategies, the data from the eight participants who noticed the relationship between the two tasks were removed from the analyses. It is worth mentioning that these participants explicitly indicated that they attempted to recall words from the memory task to solve analogies.

The mean percentage of recall at the retrieval practice phase was 70.20 (SD = 22.32), while the mean percentage of correctly solved problems was 39.31 (SD = 13.88). Neither accuracy rates during analogical reasoning nor RIF scores correlated with retrieval practice

success (r = .127, p = .574; r = -.290, p = .190, respectively). Figure 1 shows the mean percentages of correctly solved analogies and solution times as a function of the type of solution (Rp-, Nrp- and Up-).

Retrieval-induced impairment effect. A repeated-measures ANOVA on accuracy using the strict scoring procedure showed a reliable effect of type of item (Rp-, Nrp- and Up-), $F(2, 42) = 4.89$, $MSE = 995.14$, $p = .01$, $\eta_p^2 = .189$. T-tests confirmed that participants came up with fewer Rp- items (M = 37.37, SD = 18.32) than Nrp- items (M = 49.49, SD = 16.7) to solve analogies, $t(21) = -2.767$, $p = .012$, $d = 0.69$. Nrp- solutions (M = 49.49, SD = 16.7) were more produced than Up- solutions (M = 38.38, SD = 19.31), $t(21) = 2.499$, $p = .021$, $d = 0.62$, which again demonstrates the effect of exposing potential solutions to participants. Also like in Experiment 1, no statistical difference was observed between Rp- (M = 37.37, SD = 18.32) and Up- solutions (M = 38.38, SD = 19.31), $t(21) = -.249$, $p = .806$, $d = .05$, indicating that even though Rp- items were presented at study, they behaved as if they had never been presented in the context of the experiment. The ANOVA performed on accuracy when applying the lenient scoring criterion also showed a reliable effect of item type, $F(2, 42) = 9.14$, $MSE = 1060.60$, $p = .001$, $\eta_p^2 = .303$. Follow-up analysis showed that participants generated fewer Rp- items (M = 42.93, SD = 16.19) as solutions to the analogies compared to Nrp- items (M = 56.57, SD = 14.10), $t(21) = -4.29$, $p = .000$, $d = 0.90$. In addition, Nrp- items (M = 56.57, SD = 14.10) were reliably

more generated as solutions than Up- items (M = 47.47, SD = 17.88), $t(21) = 3.15$, $p < .005$, $d = 0.57$, which again reveals a priming effect in analogical problem solving. Finally, there was no reliable difference between Rp- (M = 42.93, SD = 16.19) and Up- items (M = 47.47, SD = 17.88) ($t(21) = -1.25$, $p = .22$, $d = 0.26$). Hence, the retrieval-induced impairment on studied but unpracticed items was comparable to the effect of not presenting these items for study.

The ANOVA performed on reaction times failed to show a significant effect [$F(2, 42) = 1.19$, MSE =11552788.20, $p = .165$, $\eta_p^2 = .082$; Rp-: M = 6773.50, SD = 3144.04; Nrp-: M = 8189.96, SD = 1950.71; Up-: M = 7216.01, SD = 3849.35]. The same null effect emerged when using the lenient scoring criteria [Rp-: M = 8633.51, SD = 2986.51; Nrp-: M = 9515.41, SD = 4004.48; Up-: M = 9130.52, SD = 3056.44, $F(2, 42) < 1$, MSE =1748769.37, $p = .44$, $\eta_p^2 = .038$].

In summary, and replicating Experiment 1, Experiment 2 reveals that items that putatively had been the target of inhibitory control were significantly less chosen as solutions than control items in an independent analogical test. Moreover, inhibited words were produced to the same degree than unstudied (unprimed) words. Since in the present experiment additional measures were taken to minimize participants' awareness about the connection between the memory and the reasoning tasks, these results suggest that the modulation of the

accessibility by means of inhibitory mechanisms may impair analogical thinking implicitly.

General discussion

Current evidence suggests that prior exposure to relevant information can foster analogical problem solving by increasing the accessibility to appropriate knowledge (Day & Goldstone, 2011; Howe et al., 2015; Schunn & Dunbar, 1996). In the present work, we aimed to further explore the relationship between memory and analogical thinking from a different angle; namely, that reduced access to critical information may adversely affect performance on an analogical thinking task. The results of two experiments support this idea.

Capitalizing on an experimental procedure (retrieval practice) that has systematically shown to be effective to reduce memory accessibility (for a meta-analytic review see (Murayama et al., 2014), we conducted two experiments wherein participants engaged in solving analogical problems of the type 'A is to B as C is to D' after selectively retrieving part of previously encoded items. Since selective retrieval is known to lead to forgetting (a direct measure of reduced accessibility) of memories that are related to those selectively recalled, we expected selective retrieval to negatively modulate analogical thinking performance provided that the forgotten information turned out to be

relevant during problem solving. In this line, we systematically found that related unpracticed (Rp-) words were less chosen as solutions than unrelated control (Nrp-) words to solve analogies. To put it another way, the analogy problems that could potentially be solved with the less accessible items turned out to be more difficult to solve. Importantly, this was the case in two experiments even when participants were not aware that some of the solutions that they generated to solve the problems had been previously presented. Hence, the present results are consistent with others from previous studies that have examined the influence of memory control processes over performance in tests of verbal creativity (Gómez-Ariza et al., 2017), or decision making (Coman, Coman, & Hirst, 2013; Iglesias-Parro & Gómez-Ariza, 2006) (for related studies see the meta-analytic review by Storm et al., 2015). In fact, Gómez-Ariza et al. (2017) reported similar results regarding how reduced access to relevant information may impair creative thinking. In a series of experiments, participants studied a set of words and then repeatedly practiced a subset of them. Finally, participants were told to solve problems from a Remote Associates Test (RAT). The RAT is a creativity verbal test in which solvers are presented with three unrelated words and they are asked to find a fourth word that is associated with the three unrelated presented words (e.g., for fish-mine-rush, a correct solution could be gold). Words that had previously been the putative target of inhibitory control (by virtue of selective retrieval) were generated to a

lesser extent than creative solutions relative to baseline items. Therefore, all these studies are informative of how reduced accessibility to relevant information may impact on thinking, with the present experiment demonstrating for the first time that this also applies to analogical reasoning.

As previously mentioned, a remarkable point of the present experiments is that they were designed to keep participants' awareness of episodic retrieval to a minimum during problem solving. Analogical thinking has often been viewed as an intentional analytic process (Anolli et al., 2001). People must deliberately search through potential, and often irrelevant, solutions in memory that can be implemented to the current situation. As mentioned, some have argued that the presence of explicit cues are required to apply previously activated potential solutions to analogical problem solving for successful transfer (Cohen et al., 1997; Reber et al., 1996). However some studies also suggest analogical transfer could also occur without explicit cues and without awareness that potential solution was previously presented (Day & Gentner, 2007; Day & Goldstone, 2011; Gross & Greene, 2007; Howe et al., 2015; Kokinov & Petrov, 2000; Schunn & Dunbar, 1996). Along this line, the main finding of the present experiments indicates that information involved in a memory task may later influence how accurately people deal with analogical problems and, what is of special relevance here, do so unwittingly. In Experiment 1 almost all the participants reported being

aware that some of the solutions they produced were words that had previously appeared in the experimental session. However, most of them noticed the relation between the two sessions at the half/end of the test when practiced words (Rp+, and their controls Nrp+ and Up+) were presented. Hence, it seems reasonable to think that solutions produced during the first block (containing the most relevant items here: Rp-, Nrp- and Up-) stemmed from genuine analogical mapping processes rather than from retrieval strategies. Experiment 2, which was conducted after removing the second block at test, confirmed this idea by showing that only 26% of the participants became aware of the studied words to solve problems. This experiment again revealed that putatively inhibited (Rp-) solutions were less produced than control (Nrp-) solutions, even when participants who were aware of the relation between the two experimental sessions were not considered. This finding supports the idea that memory can influence reasoning unconsciously. People may attempt to access potential solutions without being aware that their particular memory state (determined by previous retrieval dynamics) may be guiding the current process of problem solving. As a consequence, reasoning may be disrupted by a temporary reduced access to potential solutions in memory.

While a few situational factors might potentially reduce accessibility to relevant information during problem solving (e.g., short encoding time, blocking by other more salient information), the

impairment in analogical problem-solving observed in the present experiments may be understood as an aftereffect of inhibitory control during selective retrieval (Anderson, 2003; Storm & Levy, 2012; Weller et al., 2013). By this view, inhibition is an adaptive control mechanism that temporarily downregulates competing memory representations to overcome retrieval interference over target memories, with a wealth of data from behavioral (e.g., Román, Soriano, Gómez-Ariza, & Bajo, 2009; Schilling, Storm, & Anderson, 2014; Weller et al., 2013) and brain-related studies supporting this view (e.g., Kuhl, Dudukovic, Kahn, & Wagner, 2007; Stramaccia, Penolazzi, Altoè, & Galfano, 2017; Waldhauser, Johansson, & Hanslmayr, 2012; Wimber, Alink, Charest, Kriegeskorte, & Anderson, 2015). Hence, if the suppressed information turns out to be later relevant and access to it is required, impairment in the ability to come up with such information is to be expected, regardless of the situation requiring its use.

Although an interference-based account of retrieval-induced performance impairment have been proposed in the context of episodic memory testing (Jonker, Seli, & MacLeod, 2013; Raaijmakers & Jakab, 2013), the main present finding represents a serious challenge for such a view (see also Gómez-Ariza et al., 2017; Weller et al., 2013). Thus, for example, it has been proposed that associative blocking rather than inhibition could be the mechanism that underlies such impairments (Raaijmakers & Jakab, 2013; Verde, 2012). The idea is that because

retrieval practice strengthens the relation between the retrieval cue and the practiced (Rp+) items relative to the strength of the unpracticed (Rp- and Nrp-) items, if the cue is presented in a later test, practiced items' memories would have a greater probability of being activated and will compete with their related (Rp-) memories so as to block their retrieval. This account, however, is not able to accommodate findings of retrieval-induced performance impairments observed with testing procedures that do not, either overtly or covertly, allow for the use of the memory cues provided during the retrieval practice phase (see Weller et al., 2013, for a discussion of this issue). As a matter of fact, the separate analyses of the performance of the (eight) participants who reported being aware that the studied/practiced words could be used to solve the problems revealed that thinking back on these words tended to enhance rather than hinder performance (for related results see Weller et al., 2013). Hence, since in our experiments (Experiment 2 in particular) participants were tested with analogical problems and presented with items that were totally unrelated to the practiced items, it would seem odd to claim that blocking from the more recently processed (Rp+) items was taking place during the contextually unrelated analogical thinking phase. The implicit memory nature of the testing procedure of Experiment 2 supports further the interpretation that it was memory inhibition what hindered analogical problem solving (see Gómez-Ariza et al., 2017(Gómez-Ariza et al., 2017)(Gómez-Ariza et al., 2017)(Gómez-

Ariza et al., 2017)(Gómez-Ariza et al., 2017)(Gómez-Ariza et al., 2017)(Gómez-Ariza et al., 2017)(Gómez-Ariza et al., 2017) for a similar interpretation applied to verbal creativity). Moreover, the inclusion in the final test of analogies whose possible solutions were items that had never been presented in the context of the experiment enables us to precise the degree of inaccessibility that selective retrieval may cause on problem solving. Since participants came up with suppressed (Rp-) solutions as little as they did with unstudied (unprimed; Up-) solutions, it seems that executive control at retrieval may downregulate competing memories by rendering them as if they had not been recently encoded. Thus, while it does not seem to be the case that problem solving may be generally affected by selective retrieval (Nrp+ solutions were more produced than unprimed Up- solutions), it seems reasonable to put forward that inhibitory control during retrieval may lessen accessibility of some potential solutions.

Of course, at first sight, one might have expected generation of Rp- solutions to be even lower than that of Up- solutions because of inhibitory control. However, it should be noticed that Rp- items differ from Up- items in that they were previously presented in the context of the experiment during the study phase (in addition to being the target of inhibitory control). Hence, Rp- items would enjoy some benefit from this previous exposure (a 'priming' effect). If so, inhibition would be expected to take from them this benefit reducing their accessibility to the level of

non-exposed items. Future experiments where perceptual and lexical priming from previous exposure is avoided should be conducted to further support this interpretation.

An additional point that deserves attention is that we observed the same pattern of retrieval-induced impairment with different (strict vs. lenient) scoring procedures, which is suggestive of how inhibitory control worked during selective retrieval practice. Because the tolerant criterion involved accepting as correct items that did not exactly match the studied items (i.e., synonymous or semantically related words), the fact that participants also solved less Rp- than Nrp- analogies when considering this less strict criterion suggests that inhibitory control during selective retrieval not only affects episodic memory, but also may affect general semantic representations (for a similar idea on a related memory inhibition phenomenon, see Taubenfeld, Anderson, & Levy, 2018).

While our main finding unveils the negatives consequences of memory control mechanisms on problem-solving solutions accessibility, previous work has already shown that inhibitory control recruited during problem solving may also have the potential for facilitating performance by preventing interference of irrelevant information. Thus, for instance, in the context of creative problem solving, Storm, Angello, and Bjork (2011) used a problem-solving-induced forgetting paradigm

in which participants were exposed to cue-response pairs (e.g., lick–tongue, sprinkle–rain) and then were asked to solve RAT problems. Critically, half of the cue-response pairs contained misleading associates for the RAT problems designed to interfere and cause fixation (i.e., lick, sprinkle, mines) whereas half of the RAT problems did not (i.e., manners, tennis, round). Performance in a final cue-response test showed that participants recalled fewer response words associated with cues that appeared during the problem- solving phase than response words associated with cues that did not appear during the problem-solving phase. Thus, attempting to solve a problem caused participants to forget irrelevant information in order to deal with interference from competing misleading associates. Similarly, metaphor processing may share similar features with problem solving suggesting a link between overcoming interfering irrelevant information and inhibitory control. George and Wiley (2016) conducted a series of experiments using a metaphor-induced lexical forgetting paradigm, in which participants studied word pairs composed on potentially metaphoric vehicles cues and literal associate targets (e.g. SHARK–swim). Then, participants read and interpreted half of the vehicles as part of metaphoric sentences (e.g. The lawyer for the defense is a shark). On a test of final recall for all of the initially studied word pairs, participants showed reduced recall for word pairs consisting of vehicles and their literal associates. These results suggest that, in order to arrive at the figurative meaning of a metaphor,

literal irrelevant associated information that is previously activated may have to be inhibited. As a consequence of attempting to retrieve the figurative target meaning from memory, recall for literal information is impaired. Therefore, the relationship between memory control processes, such as inhibition, and problem solving may depend on which specific information is the target of control. If inhibition acts on information in memory that would subsequently have to be retrieved to generate a solution, worse problem solving performance would be expected. On the contrary, if inhibition is recruited to suppress activation of irrelevant information that would otherwise interfere with problem solving, one could predict enhanced performance.

Our main findings might have applied implications, since analogical thinking is thought to be crucial in a variety of fields ranging from scientific discovery to creative problem solving. Despite the fact that analogical reasoning is a desirable tool to tackle real-world problems, a number of studies have shown that people often fail to use past knowledge to solve a problem which shares similar features (Bassok & Holyoak, 1989; Gick & Holyoak, 1980, 1983; Perfetto et al., 1983). Since performance can be influenced by how available certain pieces of information are in our memory, every single thought or mental activity done immediately before solving a problem might modulate a particular memory state. In fact, our study suggests that the consequences of certain cognitive operations over memory representations may hamper

analogical reasoning without noticing it. Although successful retrieval can facilitate the recall of wanted memories, it can also impair later access to related memories. In a more naturalistic setting, merely attempting to generate analogical solutions to a problem by discussing with other people on previous experiences could prevent us from solving the problem. For example, in a brainstorming session, wherein the main goal is to generate as many different ideas as possible, overhearing or coming up with some ideas or solutions about a particular problem might lead to inhibition of potential related solutions or ideas (Nijstad & Stroebe, 2006). To conclude, the modulation of the accessibility of information by means of an inhibitory control mechanism may have significant effects on analogical reasoning. Our study adds to a growing body of research to show that unconscious control processes related to retrieval may have an impact on high-order cognitive operations such as creative thinking (Gómez-Ariza et al., 2017) or decision-making (Coman et al., 2013; Iglesias-Parro & Gómez-Ariza, 2006). Future studies on this topic are required in order to understand the extent to which unconscious processes may influence our complex behavior.

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CHAPTER V:
Electrophysiological correlates of interference control at retrieval predict performance on a subsequent analogical reasoning task.

Experiment 3

Previous research has shown that variations in the accessibility of relevant information that stem from retrieval practice may impair analogical reasoning. In the present study, we sought to examine the neural signatures of inhibitory control during selective retrieval and its effects on a subsequent analogical reasoning task by employing electrophysiological measures. At a behavioral level, we found that selective retrieval of a subset of potential solutions led to impaired performance on the analogy test. ERPs analyses during selective retrieval revealed that (1) the repeated presentation of category cues was associated with decreased amplitudes for the FN400 ERP effect, possibly reflecting reactivation of competitor associates and interference; (2) this effect correlated positively with the retrieval-related impairment in analogical reasoning performance. During the analogy test, the production of control solutions (non-affected by prior retrieval practice) was characterized by more positive modulations of anterior frontal and parietal ERPs than the production of unstudied solutions, whereas inhibited solutions elicited similar amplitudes than unstudied solutions. This effect was restricted to the retrieval phase of the analofy where the actual solutions had to be retrieved, but it did not affect the mapping phase where the accessibility status of the possible solutions failed to reveal significant amplitude differences. These findings suggest that control during selective retrieval may lead to the downregulation of competing memory representations and advance our understanding of the neural correlates of analogical thinking.

Introduction

Analogical reasoning, or the ability to apply relational knowledge to find correspondences among different contexts, is crucial in human cognition (Gentner, 1983). Indeed, it seems to be a core process in scientific discovery, learning, and transfer (Gentner & Smith, 2013). Reasoning by analogy involves establishing connections between non-associated ideas, which allows us to make new concepts more understandable in light of familiar things. For example, science teachers often present the spiral staircase analogy to conceptualize the structure of DNA, use a 'tree of life' to explain the branching patterns in the evolution of species or compare the cell to a factory where the organelles are the different sections of the factory (i.e. the mitochondrion as the powerhouse of the cell and the Golgi apparatus as the sorting center) (Herr, 2008).

Successful analogical reasoning is thought to comprise two main component processes; namely, retrieval of significant knowledge from long-term memory, and mapping or transfer from one domain to another (Gentner, 1983; Holyoak & Thagard, 1989). Much of the research to date has focused on mapping (Gentner & Smith, 2012), even though recent work has examined issues involving access to relevant knowledge and memory control processes during this type of inductive reasoning (Bowden, 1985; Keane, 1987; Kurtrz & Loewenstein, 2007;

Perfetto, Bransford, & Franks, 1983; Valle, Gómez-Ariza, & Bajo, 2019). The solver's ability to access potentially useful information at an appropriate moment is crucial to comprehend and use analogies. Thus, any factor capable of influencing the accessibility of relevant information from memory could affect problem solving as long as this information is required. In this regard, recent evidence has shown that both analogical and creative problem solving as well as decision making are sensitive to the degree of accessibility of crucial information in memory (Gómez-Ariza et al., 2017; Iglesias-Parro & Gómez-Ariza, 2006; Valle et al., 2019). For example, Valle et al. (2019) showed that some analogical reasoning processes might be unconsciously and adversely affected by reduced access to relevant information. In their study, they influenced the retrievability of relevant information by using an adapted retrieval practice procedure (Anderson, Bjork, & Bjork, 1994; for a review of the memory cost associated with selective retrieval practice see Murayama, Miyatsu, Buchli, & Storm, 2014) right before an analogical problem-solving task. First, participants were presented pairs of category-exemplars items (e.g. MA-Maturity, MA-Make-up, DE-Detective) to study. After this, participants engaged in cued-recall of half of the exemplars from half of the categories (e.g., MA-Mak___). Lastly, and after a delay, participants were asked to solve analogies of the format 'A is to B as C is to ?'. In these analogies, participants are expected to find the relation between the first pair of words and engage in mapping and

relational transfer to come to a solution. Many of the solutions of these analogies matched the words previously studied (e.g. '*GREED is to GENEROSITY as INFANTILISM is to ?*' whose solution was '*Maturity*'), although participants were not told about this coincidence. In addition, the test also included analogies whose solutions were not presented in the context of the study. Interestingly, the results showed that unpracticed items from practiced categories (e.g. Maturity; hereinafter referred to as Rp- items) was significantly less produced as solutions than items from control (non-practiced) categories (e.g. Detective (hereinafter Nrp items) but generated as solutions to the same extent as unstudied (baseline) words (hereinafter Up items). Importantly, participants reported not to be aware of the connection between the memory and analogy tasks. This indicates that previous memory operations may impair analogical reasoning without noticing it (for related results in creative thinking see Gómez-Ariza et al., 2017). This reduction in accessibility for some (Rp-) items in memory **may be explained as** the result of inhibitory processes during selective retrieval that act to reduce activation of competing information (Gómez-Ariza, Fernandez, & Bajo, 2012; Levy & Anderson, 2002; Weller, Anderson, Gómez-Ariza, & Bajo, 2013; Wimber, Alink, Charest, Kriegeskorte, & Anderson, 2015).

Several studies have explored the neural correlates underlying inhibitory control during selective retrieval by employing brain imaging

and electroencephalographical (EEG) techniques. Johansson et al. (2007) recorded EEG during selective retrieval practice and compared event-related potentials (ERP) during a standard competitive retrieval condition with those recorded during a re-learning condition in which retrieval was not required (nor was the need of interference control). They found positive-going ERPs over prefrontal regions to be sensitive to retrieval competition. Importantly, this stronger ERP positivity predicted individual differences in the reduced accessibility to Rp- items in a subsequent memory test. In a more recent study, Hellerstedt and Johansson (2014) manipulated the competition level during retrieval practice by modifying the associative strength between category cue and competitors. The authors reported that strong competitors elicited more positive amplitude onsetting around 300 ms after the category cue presentation over anterior and frontal electrodes. Importantly, this positive-deflection again predicted individual differences in forgetting. The authors interpreted that this ERP may reflect the reactivation of associates to the category cue, congruent with the FN400 effect observed in previous ERP studies associated with conceptual priming and old/new familiar effects, but also interference and ensuing forgetting of the reactivated competing memories.

EEG measures have also been used to examine the neural correlates of analogical reasoning (Kmiecik, Brisson, & Morrison, 2019; Long et al., 2015; Maguire, McClelland, Donovan, Tillman, & Krawczyk,

2012; Qiu, Li, Chen, & Zhang, 2008; Zhao et al., 2011). These studies typically employ four-term analogies of the form 'A:B::C:D' and participants are generally asked to verify whether the given 'D ' term ' is related to C in the same way than 'A' is related to 'B'. These analogy problems are presented into isolated substages to better evaluate the involvement of encoding (base stimuli or 'A:B' terms), mapping (target stimuli or 'C' term) and response production (conclusion or 'D' term) processes. In a non-semantic analogy task (e.g., abc:abd::ijk:ijl), Qiu, Li, Chen, et al. (2008) reported that the 'A:B' stage elicited a negative ERP deflection (N500–1000) with dipole localization at the left thalamus and a positive component (P600–1000) with dipole localization at the medial prefrontal (BA10) and the left frontal cortex (BA6)) possibly reflecting encoding and schema induction. Following the presentation of the 'C' term a greater negativity (N400-600 component) over frontal electrodes is typically elicited that has been associated with activation of the schema and analogical mapping (Maguire et al., 2012; Qiu et al., 2008; Zhao et al., 2011). Altogether, these results suggest that the encoding and mapping processes appear to be well differentiated since different components are evoked. Nevertheless, although these studies have attempted to temporally disentangle the processes involved during the different stages of analogical reasoning, none of them has examined memory dynamics making it difficult to understand its involvement during analogical processing.

The present work aims to examine the neural signatures of the effects of prior selective retrieval on analogical reasoning. Specifically, we wanted to learn to what extent reducing the accessibility of some target memories impact the mapping and/or retrieval processes of analogical problem solving. Because EEG provides high temporal resolution, we aimed to track temporal dynamics of the selective retrieval mechanism during both the retrieval practice phase, when they are assumed to operate, and during the analogical reasoning task, when its detrimental effects should be observed. To this end, we adapted the procedure employed in Valle et al. (2019), in which the retrieval practice paradigm was introduced right after an analogical reasoning task, to influence the accessibility of potential solutions while electrophysiological brain activity was recorded. At a behavioral level, we expected to replicate the main results obtained by Valle et al. (2019): namely, those solutions that putatively had been the target of inhibitory control (Rp- words) were significantly less provided as solutions than control words (Nrp) in the subsequent analogy test. In addition, inhibited solutions were expected to be generated to the same degree than unstudied or unprimed (Up) words. As in Valle et al.'s (2019) experiments, specific efforts were made to minimize participants' awareness about the relationship between the memory and the analogical reasoning task. This would support the idea that the recruitment of inhibitory control during retrieval may have an effect on a subsequent reasoning task that requires this information to be

accessible without awareness of the episodic nature of the provided solutions.

As described earlier, previous research examining the neural underpinnings of inhibitory control during selective retrieval has reported competition-sensitive ERP correlates, such as the FN400 component, that further predicted retrieval-induced forgetting. In the context of RP procedures, the FN400 has been linked to the reactivation of competing associates when the cue is presented and to the recruitment of an inhibitory mechanism to reduce interference (Hellerstedt & Johansson, 2014). Accordingly, in the present study, the repeated presentation of the category cue along cycles should result in reduced amplitudes in the FN400 component over anterior frontal regions. This amplitude reduction across retrieval attempts would reflect successful interference resolution that should correlate with the subsequent production impairment of Rp- items as solutions during the analogical reasoning task (Hellerstedt & Johansson, 2014).

We further aimed to investigate the time course of these retrieval effects during analogical reasoning by isolating the stages of problem solving. Thus, we presented sequentially the A:B, C, and ? terms of the analogy to temporally separate the neural correlates of the distinct processes involved in the reasoning task. Previous research has linked the P600-1000 components elicited during the A:B stage to scheme

induction processes (Qiu et al., 2008; Zhao et al., 2011), whereas the N400 component evoked during the C:? stage has been associated with analogical mapping (Maguire et al., 2012). Nevertheless, these studies have focused on mapping and integration processes by employing analogy decision tasks, in which the ERP correlates of solution retrieval were unclear. Electrophysiological studies examining the temporal dynamics of a target memory after the presentation of a retrieval cue have observed more positive-going ERPs for previously studied words relative to unstudied words approximately 400 ms after the onset of the stimulus (Allan, Doyle, & Rugg, 1996; Allan, Wolf, Rosenthal, & Rugg, 2001; Angel, Fay, Bouazzaoui, & Isingrini, 2010; Osorio, Ballesteros, Fay, & Pouthas, 2009). This effect has been interpreted as an ERP correlate of successful episodic retrieval. In this regard, we hypothesized that the production of Nrp control solutions should evoke more positive-going frontal ERPs relative to baseline Up solutions since the Nrp items were previously experienced during the study phase, and the Up solution had never been presented in the context of the experiment. In contrast, and in accordance with behavioral data, we expected no differences between the amplitudes elicited by the generation of Rp- solutions and baseline Up solutions. This might reflect the weakening of the Rp- representations in memory at a similar level to that of Up items, which were never presented in the context of the experiment. We expected these ERPs patterns to be evident after the presentation of the C target

and during the response time window (related to the retrieval of solutions). We also expected that reduced accessibility of specific Rp- items should not affect the mapping stage of analogical reasoning since inhibition was directed to specific items and not to the more abstract relational information needed for successful mapping. Accordingly, our approach would allow us to temporally disentangle the processes of mapping and solution retrieval during analogical reasoning.

Method

Participants

46 undergraduate students (mean age = 20.97 years; *SD* = 2.56) from the University of Granada participated in the experiment. A sample size greater than 30 participants was determined before conducting the study on the basis of the sample sizes of two relevant previous experiments; namely, the one by Valle et al., 2019 that examined the effect of selective retrieval on a subsequent analogical reasoning task (with n = 30), and the one by Hellerstedt and Johansson (2014) that examined the electrophysiological correlates of competitor activation that predict retrieval-Induced forgetting (with n = 28). Because 46 participants contacted the experimenter after calling for participation, they all formed the original sample. One participant was excluded from the study because of excessive noise in the EEG recording and an

insufficient number of trials for stable ERPs. Another participant was eliminated from the analysis because he/she indicated in the post-experimental assessment that the/she had noticed the relationship between memory and analogy tasks and applied explicit retrieval strategies to solve the analogical reasoning problems. Participants received either course credit or 12 euros for their participation, and they all signed informed consent previous to their participation.

Design

For each participant, the experiment entailed two experimental blocks ran in one session. Each block consisted of three main stages: a study phase, a retrieval practice phase, and an analogical test phase. The blocks differed in the list of words that participants studied and practiced and in the set of corresponding analogies. Both blocks were separated by a 15 min short-break.

Material

In order to obtain stable ERP waveforms, we doubled the number of items used by Valle et al. (2019) in a similar experiment. Therefore, we employed two study lists (one per block), each list contained 54 words from orthography-based categories (e.g., Maquillaje, Marinero, Matanza, Madurez, Maleta, and Manual for the category MA). For one of the lists, we employed the same material used by (Valle et al., 2019).

The other list was constructed according to the same criteria: (a) they started with their same two first letters (b) their third letter was unique (c) they were two to five syllables in length (d) they had no semantic associations with words belonging to the same category. We selected them from the Alameda and Cuetos (1995) database. As in the experiments by Valle et al. (2019), the lexical frequency of the items was controlled to ensure that the Rp- items were competitive enough to trigger inhibitory control (Anderson et al., 2004; Bajo, Gómez-Ariza, Fernandez, & Marful, 2006). Thus, each category consists of three medium-low lexical frequency words (range= 10-36, *M*= 20.04) selected to be used as practiced (Rp+), unpracticed control (Nrp+) and unprimed (Up+) items and three medium-high lexical frequency words (range= 34-98, *M*= 59.91) selected to be used as unpracticed (competing) (Rp-), unpracticed control (Nrp-) and unprimed (Up-) items. In order to reduce primacy and recency effects, four additional categories were used as fillers.

We used 108 analogical reasoning problems of the form 'A is to B as C is to ?'. Verbal analogies are commonly used in verbal aptitude and standardized psychometric assessment tests (Meagher, 2006; Schalkwyk, 2011). Part of the analogies was the same as the ones Valle et al. (2019) employed in their experiments with the addition of new ones. The relationship between the pairs of terms was based on synonymy, antonymy, part to whole, object/action, cause/effect, degree,

exemplar/category among others. The solutions to the analogies matched with each of the 108 target words described above (AVARICIA es a GENEROSIDAD como INFANTILISMO a..., whose solution would be MADUREZ; GREED is to GENEROSITY as INFANTILISM is to…, MATURITY). The set of new analogies were constructed taking into account the same criteria as Valle et al. (2019): both forward and backward associative strengths were < .20 according to Spanish free association norms (Fernandez, Díez & Alonso, 2014; Fernandez, Díez, Alonso, & Beato, 2004). This set of analogies was developed using a selection process in which the list of words to be used as solutions were compiled first, and then analogies whose solutions matched with this set of words were selected. We conducted a pilot norming study to make sure that the words to be used as solutions to the analogies matched with the other terms of the analogy and were really used as solutions by the participants. Thus, in this norming study preliminary test 45 participants were asked to produced solutions to the A:B :: C: ? analogies. We only selected those analogies that felt between 20% and 80% accuracy rates. These materials were assigned to two different lists each containing fifty-four cue-response pairs and fifty-four verbal analogies. The order of presentation of the lists was counterbalanced as well as the cue-response pairs to ensure that every category rotated throughout the different practiced conditions: practiced, unpracticed (competing and control) and unprimed.

Procedure

Participants went through two experimental blocks. Each block lasted around 1h (depending on the participant's performance) and was composed of a study phase, a retrieval practice phase, and an analogical test phase. The rationale of this division of the task was to prevent participants from studying, recalling and solving a large set of material without a break. Both blocks differed in the set of materials assigned and the number of analogies. While the first block only included analogies that could be solved with Rp-, Nrp- and Up- items, the analogies in the second block could be solved with the Rp-, Nrp-, Up-, Rp+, Nrp+, and Up+ items. The rationale for not adding all the analogies during the first block was that we wanted to ensure participants were not aware of the relationship between the memory and analogical tasks until the end of the experiment (Valle et al., 2019). This has as a consequence that the number of Rp+ items was relatively small. Before the beginning of the actual experiment, participants were told that they would participate in two different experimental tasks: the first related to memory and the second with analogical thinking. They were also told that the session will be divided into two parts, each of them containing a memory and an analogical test. They were also informed that EEG will be recorded while they were performing the experimental tasks. Informed consent was obtained from all the participants. The whole experimental session lasted

around 2h 30 min including the electrodes cap setting and removal and debriefing.

Study Phase

Participants were instructed to memorize category-exemplars pairs (MA-Madurez; MA-Maturity) for an upcoming memory test. Each pair appeared in the center of the screen for 5 s with a 1-s interstimulus interval. Filler pairs were presented at the beginning and at the end of the list to control for primacy and recency effects. The rest of the items were presented in a randomized order.

Retrieval Practice Phase

Participants had to repeatedly retrieve half of the exemplars from half of the categories by a given cue (e.g., MA-Mad___). The trials started with a fixation cross, followed by the category for 2 s (e.g., MA), a black screen for 1 s, the first three letters cue (e.g., Mad___) for 3 s, and question mark during which participants were instructed to retrieve the corresponding word in order to prevent EEG artifacts. Each word was displayed three times pseudorandomly. At the end of the task, participants engaged in an arithmetic distractor task (they had to solve basic mathematic operations; e.g., 133 – 55) for 5 minutes.

Analogy test phase

During this phase, participants were asked to solve a set of verbal analogies. The presentation of each analogy involved three parts: first, the A:B terms (e.g., AVARICIA GENEROSIDAD; GREED GENEROSITY) were presented for 3 s; then after a short interval, the C term (e.g., INFANTILISMO; INFANTILISM) appeared for 3 s as a target stimulus; finally, a question mark was presented. Participants were asked to find a solution and wait to respond until the question mark appeared. This was done in order to control for speech artefacts during the recording of the EEG signal. Before starting the analogical reasoning test, four practice trials were provided to solve the analogical problems and participants received feedback on these trials. In the second block, and in order to control for output interference, participants were presented first with the set of analogies whose potential solutions corresponded with Rp-/Nrp-/Up-. Then, they were presented with the set containing the remaining Rp+/Nrp+/Up+ items. As previously described, the first block only contained problems that could be solved with Rp-/Nrp-/Up- items. Within each set, the analogies were presented in random order for each participant. To prevent participants from attempting to solve the problems simply thinking back to the previously studied/practiced words, they were told that they were going to participate in two different experiments: One concerning memory and another one concerning analogical reasoning. Figure 1 depicts the experimental procedure for the two tasks.

At the end of the session, participants filled a post-experimental questionnaire to assess whether they noticed the connection between both memory and analogical reasoning tasks, and whether they used specific strategies during the experiment. The entire experimental session was presented on a desk computer using E-Prime 2.0 (Schneider, Eschman, & Zuccolotto, 2002).

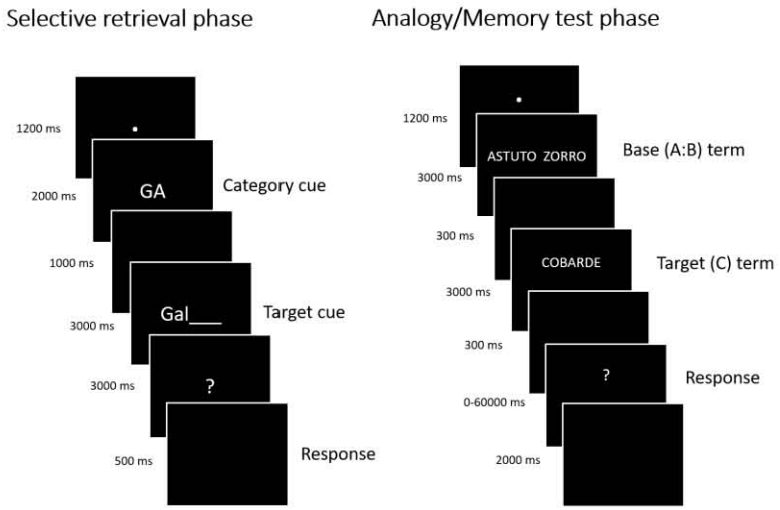

Fig 1. Experimental procedure of the selective retrieval and analogy/memory test phase.

EEG recording

Throughout the retrieval practice and the analogy test phases scalp voltages were registered by means of a 64 scalp electrode elastic cap (Quick-Cap, Neuroscan Inc.). The electrical signal was amplified with Neuroscan Synamps2 (El Paso, TX) with a .01-30 Hz bandwidth filter and a sampling rate of 500 Hz. Impedances were kept below 5 kΩ. The electrodes were referenced to the Vertex electrode (REF) during data acquisition and re-referenced offline to a common average. Additional electrodes located above and below the left eye and outside the external canthi of each eye registered vertical and horizontal ocular movements and blinks.

ERP analyses

Different ERP analyses were conducted for the different phases in which EEG was recorded: the selective retrieval phase and the analogical reasoning test. In both cases, before data analyses a high-pass filter at 1 Hz was applied and blinks, ocular movements and EKG artifacts were corrected by means of independent component analyses using the 'runica' function that can be found within the EEGLAB toolbox. The remaining artifacts were corrected by visual inspection. Bad channels with a high level of artifacts were detected by careful visual inspection and interpolated from neighbor's electrodes. Waveforms were low-pass filtered at 30Hz. Epochs were segmented into 1000 ms,

including a 200 ms pre-stimulus period used as baseline correction. On the resulting epochs, we applied an automatic artifact rejection with an amplitude threshold of ±100 μV. Finally, epochs were averaged separated for each participant and trial type. Based on previous EEG research on retrieval-induced forgetting (Johansson et al., 2007), we extracted 8 regions of interest (ROI) from the 64 channels: anterior-frontal (FP1, FPZ, FP2), left-frontal (F7, F5, F3), right-frontal (F4, F6, F8), left-central (T7, C5, C3), right-central (C4, C6, T8), left-parietal (P7, P5, P3), right-parietal (P4, P6, P8), and occipital (O1, OZ, O2).

The rationale behind our ERP analysis is as follows. On the one hand, we expected the neural mechanisms underlying selective retrieval to change across retrieval attempts. In particular, the category cue should more readily reactivate competing associates during the first cycle of practice relative to the second or third cycles, when interference would have been overcome by inhibitory control. These differences were expected to be evident in an FN400, given that this ERP component has been associated with the reactivation of associates in cued recall (Hellerstedt & Johansson, 2014) and recognition memory tests (Opitz & Cornell, 2006). Thus, a Cycle (Cycle 1 vs. Cycle 2 vs. Cycle 3) x Region (anterior-frontal vs. left-frontal vs. right-frontal vs. left-central vs. right-central vs. left-parietal vs. right-parietal vs. occipital) ANOVA of repeated measures was conducted for the selective retrieval phase on a

200-400 ms time-window. This time window was selected after visual inspection and based on previous results by Johansson et al. (2007). On the other hand, the EEG correlates of the detrimental effect that previous interference control might have on analogical reasoning was instead predicted to be reflected during the response stage of the analogical reasoning task. Therefore, we looked at the potential differences in amplitudes between Rp-, Nrp and Up solutions. We used the Up condition as a baseline for the retrieval-induced effect in analogical reasoning, since producing Up items as solutions do not involve the reprocessing of studied material. Thus, an ANOVA with the factors Status of Practice (Rp- vs. Nrp- vs. Up-) and Region (anterior-frontal vs. left-frontal vs. right-frontal vs. left-central vs. right-central vs. left-parietal vs. right-parietal vs. occipital) was conducted for the analogical reasoning test phase on a 400-600 msec time-window that was selected after visual inspection. Furthermore, a similar ERP analysis time-locked with respect to the C term onset was conducted to test our hypothesis that that ERP correlates during the mapping phase of analogical reasoning were not modulated by the practice status of the potential solutions. P-values were corrected using the Greenhouse-Geisser method when data violated the assumption of sphericity and post-hoc comparisons were corrected according to Bonferroni. Note that our analyses of practice status of the solutions were restricted to Rp-, Nrp and Up, and we did not include Rp+ items and their controls to analyze

possible facilitation effects. This was done because, in order to reduce possible awareness of the relation between the memory and reasoning phases of the experiment, we did not include Rp+ items in the analogy task presented in the first block (see procedure). Thus, given the small number of Rp+ trials, our interest in getting stable and reliable ERP effects and our focus on the aftereffects of inhibitory control, we did not analyze the EEG recordings associated with the facilitation effect.

Finally, we correlated the magnitude of the ERPs observed during the selective retrieval phase and the subsequent retrieval-induced impairment in analogical reasoning. To this end, we calculated the ERP amplitude differences between cycles during the relevant time window and clustered of electrodes with a reliable effect.

Results

Behavioral results

Both accuracy and reaction times were recorded online. Mean accuracy for the retrieval practice phase was 61.21% (*SD* = 14.82) and 42.99% (*SD* = 8.89) for the analogy test. In order to check for an inhibitory effect, we conducted a repeated-measures ANOVAs as a function of the status practice/exposition of items (Rp- vs. Nrp- vs. Up-) on accuracy. Table 1 represents the mean percentages of correctly solved analogies. In addition, and although the main focus of the experiment

was not on the facilitation effect, for completeness we also performed a repeated-measures ANOVA to check for it (Rp+ vs. Nrp+ vs. Up+), since the number of Rp+ items and their controls was sufficient for behavioral analyses.

Inhibition effect. The analysis revealed a main effect of type of item, $F(2, 90) = 29.028$, $MSE = 2997.474$, $p < .001$, $\eta p2 = .392$. Bonferroni corrected post-hoc comparisons indicated that participants solved fewer analogies with Rp- words than with Nrp- items ($p < .01$). Importantly, there was no difference between the production of Rp- and Up- items as solutions ($p = .48$), but participants solved more problems with Nrp- items than with Up- words ($p < .001$). Hence, and replicating the Valle et al.'s (2019) results, the impairment in solving analogy problems with items that had putatively been the target of inhibitory control was comparable to that of not having previously presented the potential solutions in the context of the experiment (Up- items).

Facilitation effect. The ANOVA showed a main effect of type of item, $F(2, 90) = 8.826$, $MSE = 1828.592$, $p < .001$, $\eta p2 = .164$. Bonferroni corrected post-hoc comparisons revealed that both Rp+ and Nrp+ words were significantly more generated as solutions than Up+ words (both with $p < .001$). However, the difference between Rp+ and Nrp+ did not reach statistical significance ($p = .269$).

Table 1. *Mean percentages of correctly solved analogies (and standard deviations) as a function of the Retrieval Practice Status in the previous memory practice task.*

	Retrieval Practice Status					
	Rp+	Nrp+	Up+	Rp-	Nrp-	Up-
	50.24 (15.31)	44.93 (19.03)	37.68 (14.15)	39.25 (12.14)	51.50 (13.50)	36.27 (11.73)

ERP data results

ERP Correlates of Cue presentation during Selective Retrieval

Grand means of ERPs evoked by the presentation of the category cue during the selective retrieval phase are plotted in Figure 2. There was a remarkable difference in amplitude over anterior frontal, left-parietal and occipital regions between ERPs elicited after the presentation of the category cue during the first cycle and the presentation of the same category cue in the second and third cycle. This amplitude difference has its onset about 200 ms after the cue presentation and lasts approximately until 500 ms. Based on visual inspection of the grand average waveforms, we selected the 200-400 ms time window for analyses. These analyses

revealed a reliable interaction between Cycle and Region [F(2.499, 112.437) = 3.744, MSE = 33.266, p = .019, $\eta p2$ = .077]. Post-hoc comparisons showed that the first cycle elicited a marginally significant stronger positivity than the second cycle (p = .057) and the third cycle (p = .066) over anterior frontal sites, but a stronger negativity over left parietal (p = .023, p = .014, respectively) and occipital (p = .039, p = .025, respectively) regions. The enhanced positivity associated with the presentation of the category cue during the first cycle, relative to the second and third cycle, is consistent with the interpretation that the FN400 effect reflects the reactivation of competitors. In addition, the enhanced negativity over left parietal and occipital locations across cycles may be related to the N300 component (a negative deflection over parietal and occipital areas that emerges between 300 and 400 ms after

the onset of a stimulus) that it is thought to reflect perceptual cue detection (West, Herndon, & Crewdson, 2001).

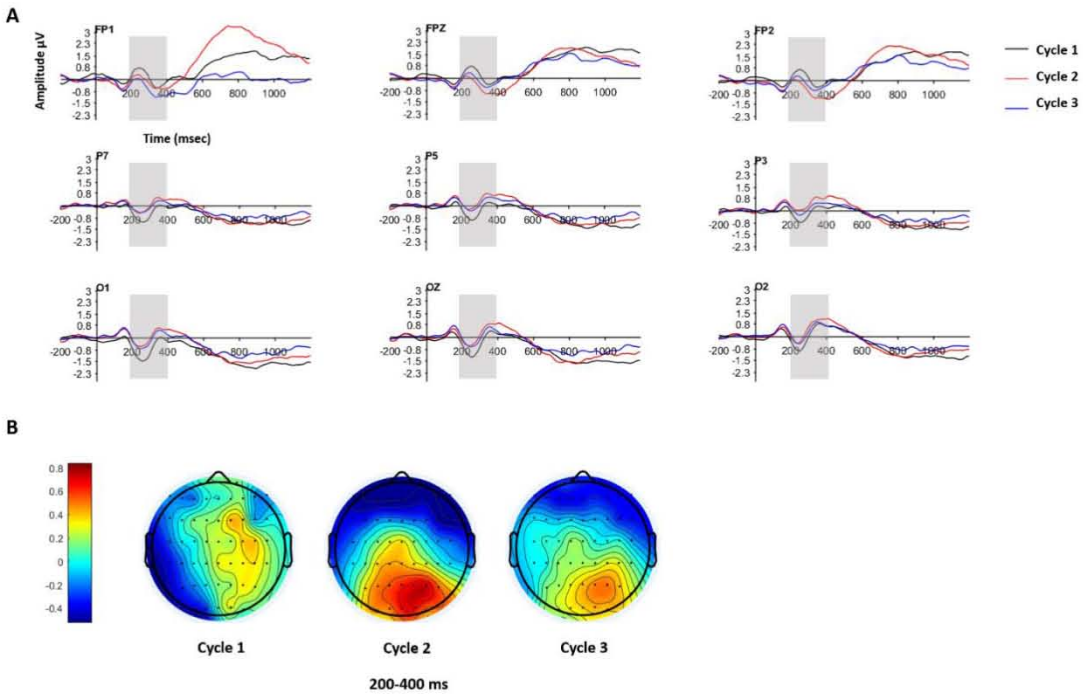

Fig 2. (A) Plot of the ERPs waveforms elicited by the presentation of the category cue in cycles 1, 2 and 3 during the retrieval practice phase for anterior frontal, left parietal and occipital electrodes (FP1, FPZ, FP2, P7, P5, P3, O1, OZ and O2). (B) Scalp maps show grand average topographies of cycles 1, 2 and 3 after the category cue presentation.

ERP Correlates of Analogical Reasoning in the response production stage as a function of practice status

Figure 3 displays the grand average waveforms evoked during the production stage of the analogy test as a function of the practice status of the solutions (Rp-, Nrp, and Up). Visual inspection of these waveforms showed that the most striking effect was a positive-going increase over anterior frontal electrodes when producing Nrp items compared with Rp- and Up items production. This effect began at approximately 300 ms and peaked at about 400 ms. For this reason, a time window ranging from 400 to 600 ms was selected for the statistical analyses that revealed a reliable interaction between Status of Practice and Region (F(2.142, 96.389) = 3.114, MSE = 44.472, p = .046, $\eta p2$ = .065). Follow-up analyses showed that the effect was restricted to anterior frontal (p = .009) and left-parietal electrodes (p = .051) indicating that Nrp- analogies elicited more positive going amplitudes than Up- problems. By contrast, and in accordance with behavioral results, no significant differences between Rp- and Up- solutions emerged.

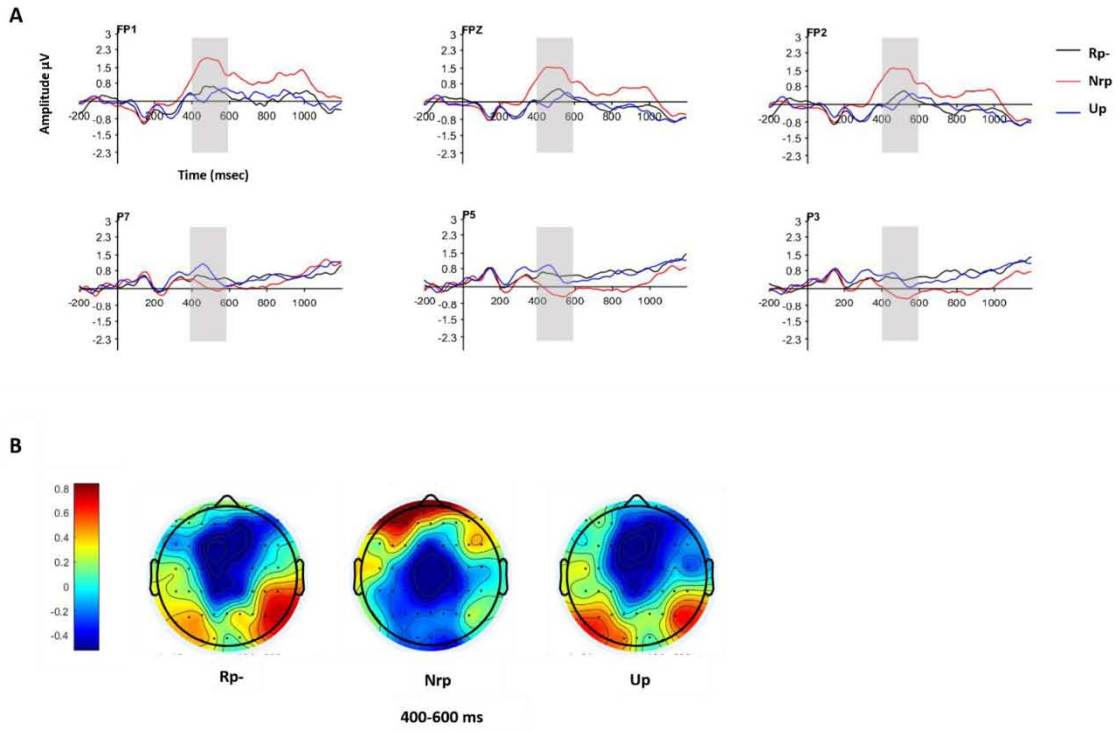

Fig 3. (A) Grand-average ERPs results for conditions Rp-, Nrp- and Up- after participants solved the analogies over anterior frontal and left parietal electrodes (FP1, FPZ, FP2 and P7, P5, P3, respectively (B) Scalp maps show grand average topographies for Rp-, Nrp- and Up- analogies during the response production stage of the test.

ERP Correlates of Analogical Reasoning in the mapping stage as a function of practice status

Figure 4 displays the grand averages waveforms elicited by the presentation of the C term during the analogical reasoning task as a

function of practice status (Rp-, Nrp-, Up-). As is evident from the visual inspection of the grand average waveforms, there were no differences in amplitude for Rp-, Nrp or Up analogies. Consistent with our predictions, in a time window ranging from 400 to 600 ms we failed to observe a significant main effect of Status of Practice ($F(1.956, 88.001) = .254$, $MSE = .030$, $p = .771$, $\eta p2 = .006$) or the interaction between Status of Practice and Region ($F(3.928, 176.779) = 1.039$, $MSE = 2.686$, $p = .388$, $\eta p2 = .023$). The later time window between 600 to 800 ms also failed to show reliable effects [main effect: $F(1.878, 84.497) = 2.023$, $MSE = .344$, $p = .141$, $\eta p2 = .043$; interaction: $F(3.151, 141.801) = 1.784$, $MSE = 8.985$, $p = .150$, $\eta p2 = .038$].

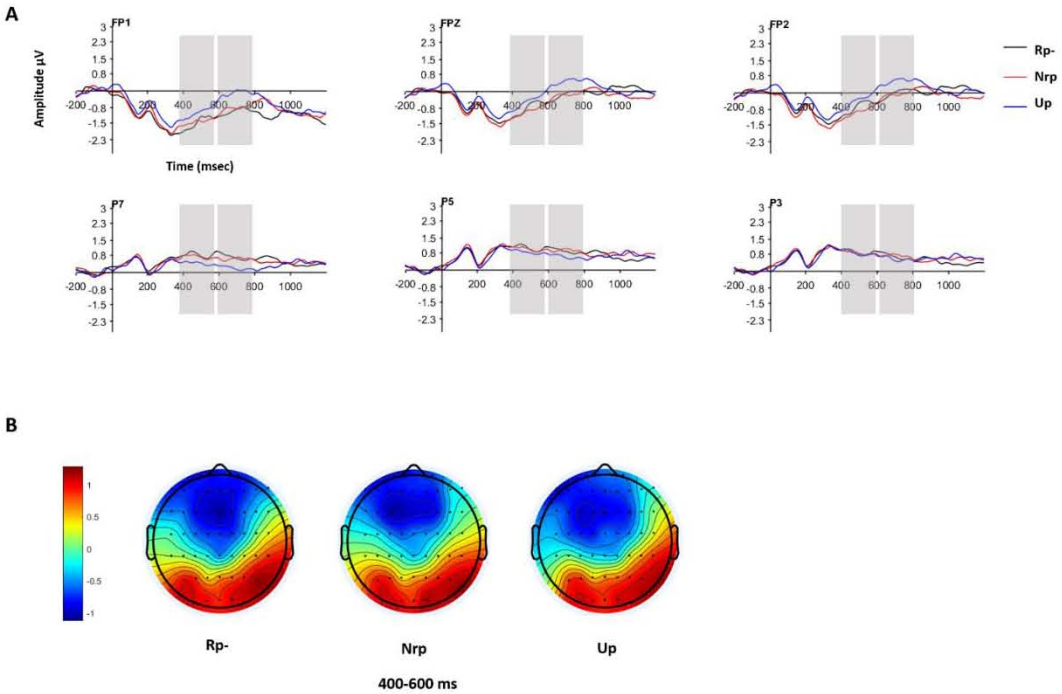

Fig 4. (A) Grand-average ERPs results of conditions Rp-, Nrp and Up after the presentation of the C term during the analogical reasoning test for anterior frontal and left parietal electrodes sites (FP1, FPZ, FP2 and P7, P5, P3). (B) Scalp maps show grand average topographies of Rp-, Nrp and Up analogies during the mapping stage of the analogy test.

Relation between Selective Retrieval ERPs Correlates and Retrieval-Induced Impairment in Analogical Reasoning.

We further explored whether the ERP amplitude differences over anterior frontal, left parietal and occipital regions between the first and

third cycles during retrieval practiced predicted the amount of subsequent impairment in the reasoning task. We calculated for each participant a RIF index by subtracting the percentage of Rp- correct solutions generated from the percentage of Nrp- solutions provided to the problems. This difference was then divided by the percentage of correct Nrp- solutions [((Nrp- – Rp-)/Nrp-) × 100]. Interestingly, we observed a reliable positive correlation between ERP amplitude differences across cycles in the anterior frontal region and the retrieval-induced reasoning impairment (r = .358, p = .014). Nevertheless, no reliable effect was found when analogical performance was correlated with the amplitude differences in the left parietal and the occipital.

Discussion

The purpose of the present study was two-fold: one the one hand, we aimed to replicate the Valle et al.'s (2019) finding that the cost of selective retrieval can be observed in an unrelated analogical reasoning task. On the other hand, we aimed to track the neural correlates of selective retrieval and its possible differential effects on analogical mapping and retrieval in the subsequent reasoning task. Since EEG can reveal changes in patterns of brain activation with a high temporal resolution, we examined ERPs to investigate the time course of control processes during retrieval as well as to identify the extent to which externally-induced reduced accessibility to relevant information

differentially affected mapping and retrieval during analogical problem solving.

The present behavioral results were similar to those observed by Valle et al. (2019) showing that, after engaging in selective episodic retrieval, participants were less likely to produce inhibited Rp- solutions in comparison to Nrp control solutions during the reasoning test. Critically, there was no difference between the generation of Rp- and Up- solutions that were not previously presented in the context of the experiment. This suggests that control mechanisms during selective retrieval modulated the accessibility of a subset of items (those competing for retrieval) that led to an impairment in the performance of analogy problems that required the use of this information.

EEG recordings during the intermediate phase of the retrieval practice procedure enabled us to explore the neural mechanisms underlying selective retrieval throughout subsequent cycles of recall attempts. There is strong evidence supporting that retrieval-induced forgetting relies on the reactivation of competing memory representations and their active suppression (Wimber et al., 2015). When higher levels of interference are thought to be elicited during the first retrieval attempt, repeated retrieval results in a lower level of interference across cycles (Anderson, 2003; Bäuml, Pastötter, & Hanslmayr, 2010; Staudigl, Hanslmayr, & Bauml, 2010). Indeed, our

results showed exactly this pattern: The presentation of the category cue elicited more frontal activation in the first cycle than it did in the second and third cycles. Moreover, this positive-going deflection was observed in a time window that was similar to that of previous studies, but it was elicited with an anterior frontal topographical distribution that parallels the FN400 component that has been associated with the reactivation of competitor associates and interference (Hellerstedt & Johansson, 2014).

The FN400 component has been also related to enhanced semantic memory representations after repeated exposure (referred to as conceptual priming; Paller, Voss, & Boehm, 2007) and old/new familiarity effects caused by the reactivation of memories previously associated with a retrieval cue in recognition tasks (Opitz & Cornell, 2006). However, in the present study, the observed FN400 effect elicited by the presentation of the category cue was sensitive to the repetitions showing less positive-modulation across cycles and, therefore, this finding is more consistent with the idea that the observed FN400 is related to interference. Thus, during the first cycle, the category cue more readily reactivated competing associates relative to the second or third cycles, when interference would have been overcome by inhibitory control. Furthermore, the fact that the magnitude of the FN400 component correlated positively with the retrieval-induced impairment observed in analogical reasoning mimics previous results showing that the FN400 predicts the ensuing forgetting of the reactivated memories

(Hellerstedt & Johansson, 2014). These findings indicate that the FN400 effect may be a marker of the memory reactivation that is crucial to triggering inhibitory control mechanisms to prevent competing items from entering awareness.

An additional goal of this study was to explore the EEG correlates of the detrimental effect that previous inhibitory control may have in analogical reasoning. With this purpose, we sought to disentangle analogical mapping and solution retrieval processes through the sequential presentation of the A:B, C and D terms. Remarkably, the mapping phase failed to reveal significant amplitude or latency differences as a function of the practice status of the solutions. This indicates that analogical mapping was not affected by the accessibility level of candidate solutions to the analogies. Note that mapping in analogical problem solving requires access to the more abstract relationship between the two domains, while our manipulation reduced the accessibility to the specific item's representations that were needed to solve the problems). Thus, the ERPs elicited during the response production stage and captured by anterior frontal and left parietal electrodes differed according to the items' practice status (induced by selective retrieval). In particular, Nrp- solutions elicited a more positive deflection than Up solutions. By contrast, the comparison of the waveforms elicited from Rp- and Up- items failed to reveal statistically significant differences in the same time window. Similar ERP amplitudes

for Rp- and Up solutions is indicative of how deeply inhibitory control during selective retrieval specifically affected competing memory representations, without influencing more abstract relational information needed for successful mapping. Thus, these findings suggest that the response production phase of analogical reasoning is particularly sensitive to changes in memory accessibility and further expands our understanding of the temporal aspects of retrieval processes influencing analogical reasoning during the response stage, but not during the mapping stage.

Notably, there are important differences between the current procedures and findings and those from previous EEG studies on analogical reasoning. Namely, these studies have typically focused on encoding and mapping sub-processes by comparing ERPs during analogy completion tasks and semantic/perceptual decision tasks that did not require analogical reasoning (Maguire et al., 2012; Qiu et al., 2008; Zhao et al., 2011). Altogether, the results of these studies show that analogical encoding and mapping are qualitatively distinct cognitive processes with topographically and temporally different ERP effects. Nevertheless, none of these studies focused on processes that may affect access to information needed to solve analogies. Hence, the adaptation of the experimental procedures in combination with electrophysiology measures seems ideal for isolating/identifying the detrimental effects that

selective retrieval may have on analogical reasoning, which would be difficult to achieve only relying on behavioral methods.

Prior ERP studies of cued recall have typically employed retrieval cues from which participants are required to retrieve information (i.e. such a three-letter word stem; ban___: → banana) to investigate differences in the neural activity evoked by studied and unstudied test words (Rugg & Allan, 2000). Our results are in line with the main finding of these studies showing a positive-going ERP modulation elicited by stems completed with explicitly retrieved studied words as opposed to unstudied words (Allan et al., 1996; Allan & Rugg, 1997; Angel et al., 2010; Fay, Isingrini, Ragot, & Pouthas, 2005; Osorio et al., 2009; Rugg & Allan, 2000). This effect typically onsets around 400 ms poststimulus, persists until the end of the epoch and is the largest over anterior electrodes. Allan, Wilding, and Rugg (1998) interpreted this effect as an ERP correlate of retrieval success in episodic memory for previously encountered material. In the present study, changes in the accessibility of potential solutions had a strong effect on subsequent analogical problem solving. The generation of Nrp solutions, which were previously studied but not repeatedly retrieved, showed a more positive-going ERP modulation in contrast with the production of Up analogy solutions, which were not previously studied in the context of the experiment. Nevertheless, the ERP correlates elicited by the generation Rp- solutions did not differ from those ERP evoked by Up solutions. Altogether, these

differences might reflect the retrieval practice aftereffect of reducing the accessibility of Rp- the memory representation as if they were not previously presented during the encoding phase in the context of the experiment. Thus, this finding is consistent with the view that inhibition leads to the downregulation of competing memory traces (Anderson, 2003), and that the aftereffect of this downregulation can be observed in reasoning tasks (Gómez-Ariza et al, 2017; Valle et al, 2019).

In sum, the present is the first study to report neural correlates of memory control during selective retrieval and its effects on a subsequent analogical reasoning task. The manipulation of accessibility of relevant information that was required to solve verbal analogy problems resulted in behavioral and electrophysiological differences. During selective retrieval, the repeated presentation of the category cue was related to reduced amplitudes for the FN400 ERP effect, which have been previously associated with the reactivation of competitor associates and interference (Hellerstedt & Johansson, 2014). Although it is not possible to obtain a direct marker of inhibition, the gradual decrease in amplitude across cycles may reflect the successful suppression of competing items in order to override interference. In addition, this effect positively correlated with the retrieval-related impairment in analogical reasoning performance, which is suggestive of how this impairment is related to interference resolution during retrieval practice. Concerning the analogy test, the production of Nrp solutions was characterized by positive

modulations of frontal and parietal ERP correlates relative Up solutions, whereas Rp-solutions elicited similar amplitudes to Up solutions. These differences may reflect the extent to which Rp- representations are weakened by inhibitory control (so that they end up reaching the activation level of unpresented items) and are consistent with the idea that control at selective retrieval leads to the downregulation of competing memory representations (Anderson, 2003). Importantly, this approach allowed us to temporally disentangle mapping from selective retrieval processes during analogical reasoning, indicating that executive control may directly affect the response stage of analogical problem solving without influencing mapping processes. These findings replicate and expand our understanding of neural temporal aspects of analogical reasoning by revealing how control mechanisms may affect memory accessibility and suggesting ERP correlates during analogical problem solving.

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CHAPTER VI

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

Experiment 4

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.

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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. (2017) 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), and 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., Gómez-Ariza, Martín, et al., 2017; 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 sham stimulation. 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.

Methods

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.

Materials

The same set of items used by Gómez-Ariza et al. (2017) 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 categories (e.g. exemplars as Detective, Delito, Debate, Desastre, Deporte, and Democracia belonged to the orthographic category DE). In addition, two more categories were used as fillers to control for primacy and recency effects. Each exemplar started with their same two first letters to the category as part of, did not share the third letter nor any semantic associations between the items in the same category. 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 unpracticed items from practiced categories (hereinafter Rp- items), unpracticed-control (Nrp items) and unstudied (Us) items (hereinafter unpracticed, control and unstudied items respectively) and three low-medium frequency words (range = 10–36, M= 20.15), words were selected to be used as practiced (Rp+) items 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-FA) to counterbalance the material across participants, so that every category (and exemplar) appeared in every condition of practice (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. Associative strength between the pairs of words was controlled (forward and backward associative strength < .20) according to Spanish free association norms (Fernandez, Díez, & Alonso, 2014).

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)

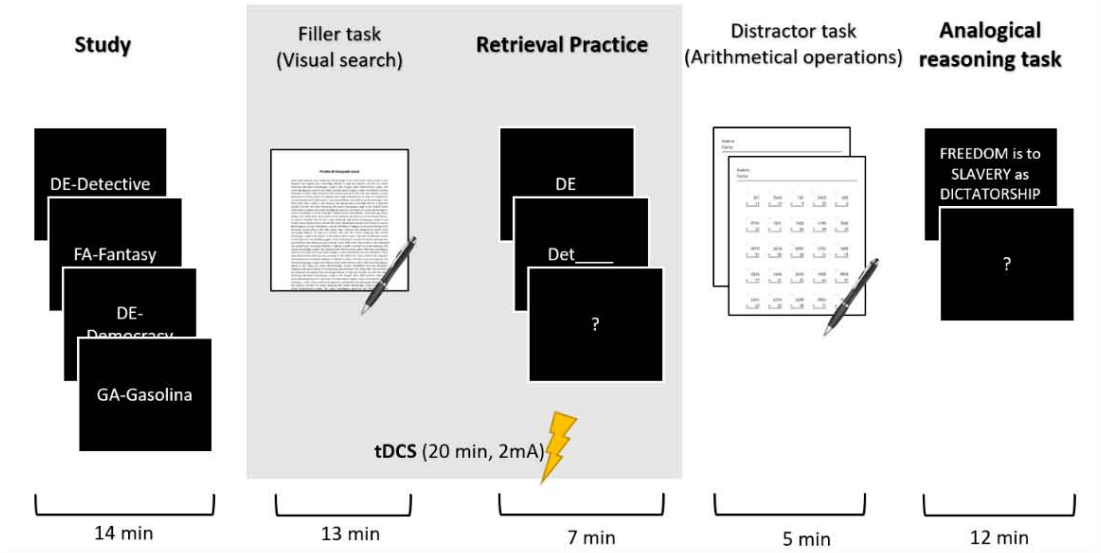
following the international 10–20 system procedure for EEG electrode placement. The anodal electrode was placed on the contralateral shoulder. In the sham group we used the same electrodes montage and current intensity, but the stimulation only lasted 30 s with an 8 s fade-in and fade-out ramp. Participants were never told about the stimulation condition they received.

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. During encoding, participants were asked to pay attention to the orthography-based category and exemplar pairs. Each pair 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. 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. 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, the experimental analogies 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 the items from the previous phases, an only block containing analogies whose solutions corresponded with the unpracticed, control and unstudied items was presented (see Valle et al., 2019). Three counterbalanced versions of the test were created so that each analogy appeared equally in every status practice 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.

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 marginally significant (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.

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, η_p^2 = .23. A main effect of stimulation was also found, $F(1,38)$ = 5.85, MSE = 2594.14, p = .02, η_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 $t(19) < 1$, $p = .70$, $d = .09$. Importantly, the lack of effect in the cathodal group did not result from baseline deflation, since the two groups exhibited similar performance when solving analogies with Nrp items ($t(38) = -.817$, $p = .42$, $d = .26$). Hence, cathodal stimulation of the right DLPFC affected analogical reasoning in a very specific way, since it only elicited mores correct responses to problems that could be solved with Rp- items. The direct comparison of both groups in the percentage of correctly solved analogies with Rp- items confirmed a better performance in the cathodal group than in the sham group ($t(38) = -3.11$, $p < .01$, $d = .98$.

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: $F(1,38) < 1$, $MSE = .10$, $p = .99$, $\eta_p^2 = .00$.

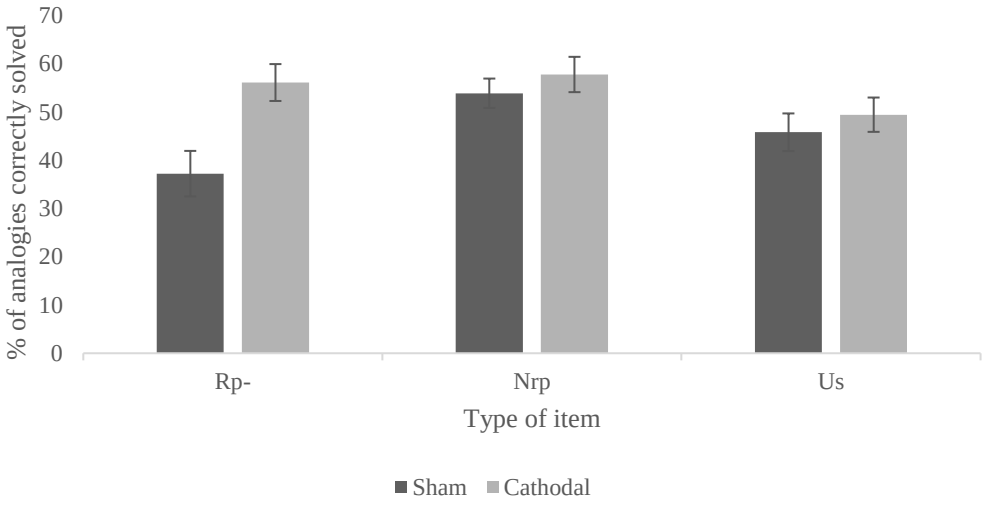


Figure 2. Performance on the analogical reasoning test as a function of stimulation and type of item. Rp- = Unpracticed solutions from practiced categories that competed for retrieval during practice; Nrp = Unpracticed (control) solutions from non-practiced categories; Us = Unstudied (control) solutions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

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, Martín, et al., 2017; 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; 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 studies that point to the right (dorsal and ventral) lateral prefrontal cortex as a source of topdown control of retrieval processes (Kuhl et al., 2007; Wimber et al., 2008, 2009, 2015).

It is worth noting that we did not observe a general effect of tDCS on analogical reasoning, given that the Nrp and Up 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, Martín, et al., 2017; 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 partially 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 a number of relevant differences exist between the present experiment and that one by Penolazzi et al., (2014) since they

used a bilateral electrode montage and an explicit memory test to examine the cost of selective retrieval. It is even more remarkable that in their study cathodal tDCS affected Nrp (control) items while left Rp- items unchanged, which seems hard to interpret in terms of genuine modulation of topdown control and largely differs from our main finding (i.e., cathodal tDCS selectively affected Rp- items). 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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PART III

General discussion and conclusions

CHAPTER VII

General discussion and conclusions

In daily life, we are frequently confronted with analogies. During the course of a single morning, people naturally use analogies for clarifying and explaining things, by comparing two different ideas to highlight similarities, or for solving a problem by mapping a solution onto a, to some extent, similar problem. However, people often fail to spontaneously access and apply analogous relevant information to reach a solution to a novel problem (Gick & Holyoak, 1980, 1983; Perfetto, Bransford, & Franks, 1983). A large body of research has sought to elucidate factors that constraint access and mapping of analogical solutions such as superficial or structural dissimilarity (Novick & Holyoak, 1991; Trench & Minervino, 2015) or the presentation of incidental hints (Gick & Holyoak, 1980, 1983). Nevertheless, the factors described in these studies do not directly address whether memory retrieval may further affect the solver's ability to reason by analogy.

An alternative and complementary tentative explanation of the eventual failure to reach analogical solutions may be elaborated from our understanding of how human memory operates. Specifically, the studies included in this thesis aimed to look into some memory processes that modulate the accessibility of relevant knowledge while reasoning analogically. Hence, in Experiments 1 and 2 we used an adapted version of the retrieval practice paradigm to investigate whether the production of potential analogical solutions may be influenced by inhibitory memory control. After confirming this to be the case at the behavioral level, in Experiment 3, we aimed to elucidate the time course of the retrieval-induced impairment effect observed on analogical reasoning by using electrophysiological measures. Thus, we explored the temporal dynamics underlying brain processes rather than indirectly measuring hindered performance in a subsequent analogy test. To this end, we applied an event-related potential approach that provides an excellent temporal resolution and would help to disentangle analogical mapping from memory retrieval. Thus, brain activity measures were obtained both during selective retrieval, at the time these processes are assumed to operate, and during the analogical reasoning task, at the time the detrimental effects of retrieval practice are observed. Finally, in Experiment 4, in an attempt to shed some light on the neural substrates of the mechanisms underlying the reduced accessibility of relevant knowledge during analogical reasoning, we used a neuromodulation

technique. Transcranial direct current stimulation (tDCS) provides the opportunity to obtain causal evidence of the role of specific areas, such as the right DLPFC, in memory control. The logic behind it is simple: if the stimulated region (either by itself or within a network) plays a role in controlling memory accessibility, then modulating its activity via tDCS should influence access to relevant information in memory without affecting analogical mapping processes.

In the following paragraphs, we will sum up the presented studies by detailing the empirical findings obtained across experiments and discussing their implications for inhibitory memory control and analogical reasoning.

Memory control dynamics: Implications for analogical reasoning

In the present work, we examined whether analogical reasoning could indeed be influenced by retrieval-related control processes. In four experiments, participants solved analogical problems of the type 'A is to B as C is to D' after selectively retrieving part of previously studied items. Selective retrieval has been demonstrated to facilitate later recall of

practiced items and induce forgetting of memories that are related to those previously recalled. Hence, we expected analogical reasoning performance to be hindered by selective retrieval when the forgotten information turned out to be later relevant to solve analogical problems. We systematically found across studies that words (Rp-) that had been previously inhibited in an unrelated memory task were less likely to be chosen as solutions, in comparison to control (Nrp-) words, when solving analogies. That is, performance during analogical problem solving was influenced by the accessibility status of potential solutions. This finding is consistent with others from previous studies that have examined the influence of memory control processes over performance in tests of verbal creativity (Gómez-Ariza et al., 2017) and decision making (Iglesias-Parro & Gómez-Ariza, 2006). Altogether, they indicate that reduced accessibility to relevant information in long-term memory may negatively impact on complex thinking, with the present work describing for the first time its application to analogical reasoning.

While Experiments 1 and 2 focused on establishing a procedure for studying the impact of previous selective retrieval on analogical reasoning and exploring the behavioral effects of reduced accessibility of relevant information on analogical reasoning, Experiments 3 and 4 tried to disentangle the neural basis of mapping and retrieval processes and whether previous selective retrieval affected one or the two processes. While a number of neuroimaging studies have focused on the mapping

stage of analogical reasoning, little attention has been devoted to the other key component, memory retrieval (Hummel & Holyoak, 1997). In fact, it is still unclear whether mapping and retrieval are in fact distinct and separable processes (Green, Fugelsang, Kraemer, Shamosh, & Dunbar, 2006; Green, Kraemer, Fugelsang, Gray, & Dunbar, 2012; Krawczyk, Mcclelland, Donovan, Tillman, & Maguire, 2010; Wendelken, Nakhabenko, Donohue, Carter, & Bunge, 2008). Hence, the findings from Experiments 3 and 4 have considerable implications in the dissociation between mapping and retrieval processes during analogical reasoning. Since EEG measures allow for temporal dissociation of brain activity that may be theoretically associated with cognitive activity, in Experiment 3 we explored the neural time course of analogical problem solving in an effort to dissociate between the two processes. Thus, analogy problems were presented in different stages: encoding and schema induction (A:B), relational mapping and inference (C), and response-related processes (D) during the time course of analogical problem solving (Kmiecik, Brisson, & Morrison, 2019). Previous EEG studies mostly focused on analogical mapping stages by comparing the processing of valid or invalid analogies (Maguire, McClelland, Donovan, Tillman, & Krawczyk, 2012; Qiu, Li, Chen, & Zhang, 2008; Zhao et al., 2011). In contrast, we were interested in the retrieval of relevant information. Thus, we hypothesized that differences in the accessibility of potential solutions should be reflected in EEG signals right after the

presentation of the C term when participants were trying to retrieve the specific information that would enable them to provide a response, and that our accessibility manipulation would not affect the mapping stage where between-domains relational information was critical. Consistent with our predictions, mapping processes were unaffected by the retrieval practice manipulation but the effects were clear at the response stage where retrieval of a specific response has to take place. Thus, the inhibited Rp- representations were characterized by EEG amplitudes that were similar to those of the non-studied (Up) items over anterior frontal and left parietal electrodes. Importantly, because Up items were never presented in the context of the experiment, the fact that attempts to retrieve Rp- solutions produced EEG patterns that were similar to those produced by completely new information supports that inhibition acted to reduce Rp- activation to the level of never-presented information. In contrast, the production of control (Nrp) non-inhibited solutions evoked positive-going waveforms relative to Up solutions. In sum, and going beyond prior studies, the present EEG results suggest that the retrieval-induced impairment in analogical performance is related to qualitatively different patterns of brain activity during the response stage, and that this impairment seems not to affect the mapping process.

In this line, in Experiment 4 we delivered tDCS over the right DLPFC on the basis of previous fMRI studies that have suggested the role

of this region within a broader network contributing to retrieval (i.e., Kuhl, Dudukovic, Kahn, & Wagner, 2007; Wimber, Rutschmann, Greenlee, & Bäuml, 2009) as well as to interference control in analogical reasoning (i.e., Bunge et al., 2005; Hammer et al., 2019; Hobeika et al., 2016). The results of this experiment showed that whereas in the sham condition Rp- words were less likely to be chosen as solutions than Nrp words were, in the cathodal condition the impairment for Rp- solutions did not show up. This indicates that active stimulation of the right DLPFC disrupted interference control during selective retrieval that later impacted on the production of potential solutions during problem solving. Importantly, we failed to observe stimulation-related changes in performance for those analogy problems that could be solved with control (Nrp and Up) items, which were generated at the same level in the two stimulation conditions. Hence, these results seem to indicate that altering neural activity in the right DLPFC does not modulate the mapping component of analogical reasoning. Rather, they join others to support its contribution in retrieval control during analogical thinking (i.e., Bunge et al., 2005; Hammer et al., 2019; Hobeika et al., 2016).

Overall, the obtained pattern of results with both EEG and tDCS methods extend the results of previous studies investigating the neural mechanisms underlying analogical reasoning by disentangling selective retrieval from mapping processes. Namely, the temporal approach used in Experiment 3 (in which analogical reasoning was probed by the

sequential presentation of the different stages involved in this type of reasoning) and the neuromodulation used in Experiment 4 (to influence the engagement of cognitive control brain areas) provided valuable information suggesting that the retrieval-induced impairment observed on analogical reasoning performance is dependent of brain regions involved in controlled retrieval. This is consistent with the involvement of specific memory retrieval rather than analogical mapping processes.

On a different line, Experiments 1 to 4 also provided evidence that some of the processes leading to analogical reasoning might occur implicitly and without awareness. Our data suggest that the retrieval-induced impairment observed in the present experiments occurred outside the participants' consciousness. In our procedures, we took care that the participants perceived the memory and reasoning tasks completely unrelated and that they did not notice the relation between both. Evidence that we succeeded in making participants unaware of this relation was the fact that they were not better at performing the analogies that could be solved with Rp+ words. It could be argued that participants noticed the relation between the two tasks and that they used an explicit memory retrieval strategy, based on their awareness of this relation, to come up with the correct solution to the analogy. If so, this strategy would have especially benefited the experimental block in which analogies could be solved with Rp+ items. However, this was not so and Rp+ facilitation was not evident. Note that Rp+ items were repeatedly

recalled during the selective retrieval phase and therefore they would especially be noticed by the participants during the reasoning task as having appeared in the memory task. However, special efforts were made to prevent participants from applying this strategy and to detect if they did so: (1) the memory and analogical reasoning tasks were presented as unrelated tasks, (2) at the end of the experiment, participants filled out a questionnaire in which they were queried about their noticing of the link between both tasks and the strategies used to solve the analogies; participants who were aware of the relation between the tasks were removed from the analyses (3) a set of analogies whose solutions were not presented in the context of the study phase was included so that finding the solution in episodic memory would be harder, (4) analogies that could be solved with Rp- items were previously presented in a separated experimental block from those that could be solve with Rp+ items, and (5) in Experiments 2 and 4 the block that contained Rp+ solutions to analogies was removed. It was only in Experiment 1 when most of the participants (73.33%) reported being aware of the link between the two tasks. Nevertheless, they claimed to notice such a link when some of the solutions matched the practiced items during selective retrieval (at the end of the analogy test). Since participants were to solve Rp- and Nrp- analogies first, those who reported being aware of the relation between tasks might have noticed it while solving Rp+ analogies. However, in Experiment 2 (and 4) the experimental block including

analogies whose potential solutions were Rp+ items, was removed from the test to examine whether analogies were solved without explicitly thinking back on previously studied items. Corroborating this idea, the results showed that only a low percentage of the participants (26%) were aware of the use of the studied words during the analogy test. From these experiments on, additional care was taken when providing the instructions to participants to present both the memory and analogical reasoning tasks as unrelated tests following distinct goals and hypotheses. In Experiment 3, only a participant out of a total of 46 became aware of the relation between the tasks and was removed from the analyses. In Experiment 4, in which no Rp+ set of analogies was included, none of the participants claimed to be aware of any link between both tasks. Overall, this finding further supports the interpretation that analogies were solved without awareness of retrieval of previously studied items. This finding contrasts with the idea that awareness is necessary for analogical transfer and that is supported by the consistent failures to observe spontaneous analogical transfer and by the fact that providing participants with explicit cues about relevant information when solving a problem may greatly increase transfer (Gick & Holyoak, 1980, 1983; Novick & Holyoak, 1991). Hence, our findings agree with those from previous studies that found implicit application of knowledge across different types of analogy problems (Day & Gentner, 2007; Day & Goldstone, 2011; Gross & Greene, 2007; Schunn & Dunbar,

1996) and are suggestive of how modulating the accessibility of previous knowledge can influence analogical reasoning without awareness of how potential solutions are retrieved.

Retrieval-induced forgetting in analogical reasoning tasks: Implications for memory inhibitory control accounts

Across studies, we provide substantial evidence that suppressing irrelevant information in the context of a memory task may later influence its accessibility on reasoning tasks unwittingly. The generalization of this retrieval-induced impairment to reasoning settings provides further support to the idea that inhibitory control is engaged during retrieval to suppress and render temporally inaccessible competing memory representations to facilitate access to target memories (Anderson, 2003). In principle, one might argue that the retrieval-induced impairment observed here in an analogical reasoning task can be explained in terms of interference (a passive mechanism) rather than inhibition (a goal-directed process) (Raaijmakers & Jakab, 2013; Verde, 2012). Namely, interference-based explanations suggest

that retrieval-induced forgetting occurs when the association between a subset of items (Rp+) and their retrieval cues are strengthened by retrieval practice. As a consequence, when the same cues are presented during the final memory test, the retrieval of practiced items may be facilitated, which in turn may block access to related but unpracticed (Rp-) items. Nevertheless, some authors have proposed that this blocking effect should be eliminated if participants are probed with different cues that the ones previously used during selective retrieval (Anderson & Spellman, 1995). The logic behind this method is that novel retrieval cues should not elicit retrieval of Rp+ items, preventing blocking effects from arising. Indeed, a number of studies have examined this prediction by testing memory with independent cues in the context of retrieval-induced forgetting and provided evidence of task- and cue-independent forgetting (Anderson, 2003; Bajo, Gómez-Ariza, Fernandez, & Marful, 2006; Gómez-Ariza, Fernandez, Bajo, & Gómez-Ariza, 2012; Levy, McVeigh, Marful, & Anderson, 2007; Weller, Anderson, Gómez-Ariza, & Bajo, 2013). Thus, this account cannot accommodate the retrieval-induced impairments observed here across experiments. Since the participants' ability to retrieve relevant information during reasoning was tested by unique analogy problems specially created for each of the words studied in the context of the experiment, and no Rp+ solutions were required to be produced in Experiments 2 and 4, the present results support an inhibitory account and are difficult to reconcile with the

strength-based proposal since these conditions make almost impossible to elicit retrieval of practiced items (see Weller et al., 2013).

It is also remarkable that a novel contribution of the present experiments is that the analogy test included a set of problems whose solutions did not match any of the previously studied words. These unprimed or unstudied solutions to the analogies served as a complementary baseline condition to better understand the after-effect of selective retrieval on the accessibility of competing information. Given that across experiments the production of suppressed solutions was similar to that of unprimed solutions, our results suggest that inhibitory control at retrieval can lower the accessibility of competing memories rendering them as if they had not been recently studied in the context of the experiment. Hence, and considering that unprimed solutions did not benefit from previous exposure that Rp- or Nrp solutions had, the comparison between unprimed and Rp- items provides a novel index to specify the degree of the inaccessibility that selective retrieval may cause on problem solving.

From a neurocognitive approach, our data strongly support the inhibitory control account that posits a role of right-lateralized prefrontal regions (mainly, DLPFC, VLPFC, and ACC) in controlling episodic retrieval by resolving interference between representations (Kuhl et al., 2007; Wimber, Alink, Charest, Kriegeskorte, & Anderson,

2015; Wimber et al., 2008, 2009). Neuroimaging studies have shown that the right DLPFC is recruited when there is a need to overcome prepotent memories or to resolve response competition (Kuhl et al., 2007; Wimber et al., 2009). Moreover, the activity of this region predicts subsequent retrieval-induced forgetting (Bäuml, Pastötter, & Hanslmayr, 2010). In Experiment 4, through stimulation, we altered the neural activity of the right DLPFC during the time that inhibition was assumed to act over competing memories, and this led to disappearance of the otherwise observed retrieval-induced impairment, so that the subsequent reasoning performance was not affected by the selective retrieval manipulation. Thus, the present results provide causal evidence of the role that the right DLPFC (within a broader network) has to implement control over episodic memories by downregulating competing representations.

We further replicated the main findings typically observed in studies of retrieval-induced suppression by recording EEG during selective retrieval in Experiment 3. As expected, we found an attenuation of the FN400 component across retrieval cycles. The first presentation of the cues evoked more positive ERPs over anterior frontal and left parietal regions compared to that observed after the second or third presentation of the category cues. Consistent with prior evidence for the involvement of this component in memory reactivation (Hellerstedt & Johansson, 2014; Opitz & Cornell, 2006), the fact of observing reduced amplitudes

across cycles may reflect the reactivation of paired associated memories, interference and the need of cognitive control in order to resolve response competition. Moreover, and also congruent with previous results (Hellerstedt & Johansson, 2014), we found that this stronger ERP positive deflection correlated with ensuing retrieval-induced impairment on analogical reasoning. In other words, the greater the FN400 effect, the greater the impairment to generate Rp- items as solutions. Therefore, this finding suggests that the FN400 component may index reactivation of memory associates that signals the need for inhibitory control to prevent them from coming to mind (Hellerstedt & Johansson, 2014). Regarding the retrieval-induced effects on the analogy test, we found that while the production of baseline unprimed solutions was associated with EEG correlates that were different from those associated with control Nrp solutions, unprimed solutions elicited similar ERP waveforms to Rp- solutions. Therefore, the present results are consistent with the assumption that inhibitory control during selective retrieval deactivates Rp- items' memory representations rendering them comparable in accessibility to unprimed items' representations, which were not presented in the context of the experiment.

Conclusions

Although people often have the opportunity to use knowledge from previous experiences or situations to solve emerging problems via analogical transfer, retrieving information that might be relevant to a problem's solution is not always an easy task. In this respect, understanding the key role that memory plays in retrieving relevant information during analogical reasoning is crucial if we seek to have a complete picture of the factors that are involved in reasoning. Across the experiments of the present work, we provided a novel experimental approach to examine how reduced accessibility of potential solutions may hinder performance on subsequent analogical problem solving unwittingly. Indeed, the observations of these studies suggest that the retrieval-induced impairment on analogical problem solving may be explained as an aftereffect of inhibitory control during selective retrieval and offers causal evidence of the dissociable contribution of the right prefrontal cortex in the retrieval processes modulating the accessibility of information. Furthermore, the findings from these experiments are indicative of mapping as a dissociable component from retrieval during the time course of analogical reasoning.

CHAPTER VIII

Future directions

During the course of my PhD, we came across new research questions and ideas for experiments that may complement the results of some of the studies presented in this work. Even though we have already started collecting preliminary data of some of these future directions, we have not included it as part of this dissertation to avoid going beyond the scope of the central questions in the thesis.

One of the questions that we run into is the implicit nature of the processes we were capturing in our analogical tasks. Although our experiments were designed to keep participants' awareness of episodic retrieval to a minimum during problem solving, a more direct proof of the implicit involvement of inhibitory effects in analogical reasoning performance would be desirable. With this purpose, we plan to manipulate the strategies that participants use to solve analogies. We would predict differences in the pattern of results when participants are explicitly instructed to use the studied words as solutions to the analogies and when they receive implicit instructions and they are not told about the connection between the memory and analogy tasks. This question is important since there is much discussion on whether analogical transfer

might be implicit in nature and on whether the consequences of memory control can be captured in implicit tasks. Hence, the results of these experiments will contribute to clarify this issue in both the memory and analogical reasoning fields. Presently, work on this issue is continuing as part of my future postdoctoral project and will be presented in future papers.

A second line of research that I started during my doctoral years is the nature of the representations accessed in memory. Although our findings add to the growing body of research that has demonstrated how changes in the accessibility of information may influence the outcomes of high-order cognitive operations such as creative problem solving (Gómez-Ariza et al., 2017), decision making (Iglesias-Parro & Gómez-Ariza, 2006) and even metaphor processing (George & Wiley, 2016, 2019), these results may be somewhat limited inasmuch such memory impairments have been studied using purely verbal stimuli. Further studies examining whether the accessibility of relevant information may also influence the items' perceptual representations in cognitive tasks that rely on visual stimuli will need to be undertaken. During my international research stay with Mark Beeman, at Northwestern University, we have already designed and run experiments examining retrieval-induced impairment on pictorial problem solving. In this task, participants are presented with camouflaged or degraded pictures and they are asked to name an object as soon as they recognize it.

Nevertheless, the preliminary results of these experiments were not completely satisfactory and we need to refine the procedure to replicate the basic findings. Thus, further studies are still required to understand whether memory for visual information may operate following similar principles than memory for verbal information.

Further work is certainly required to clarify the dissociation between mapping and retrieval as two distinct cognitive and neural processes of analogical reasoning and develop a full picture of analogical reasoning. In our studies, interference control mechanisms were engaged in a prior 'unrelated' selective retrieval task that impaired ensuing analogical reasoning problem solving. The next stage of our research will involve examining the mechanism of interference resolution during the analogical reasoning task itself, in which the retrieval candidate solutions to the analogies would be expected to recruit memory control mechanisms to override salient but misleading responses. The simultaneous use of neuromodulation techniques brain activity measurements (i.e., fMRI or EEG) would be of special interest here to further clarify the involvement of the DLPFC region in retrieval dynamics during analogical reasoning.

In sum, further work is desirable to extend our knowledge into the role of memory accessibility on analogical reasoning. Using this

knowledge and applying the new techniques and methods may provide new insights towards a link between memory and reasoning.

CAPÍTULO IX

Resumen y conclusiones

En nuestro día a día, cuando nos enfrentamos a un determinado problema, solemos utilizar soluciones que nos han resultado eficaces en otras situaciones. Sin embargo, las soluciones a estos problemas no surgen de la nada o por arte de magia, sino que suelen ser el fruto de combinaciones y asociaciones entre conceptos almacenados en nuestra memoria que aparentemente no guardan relación entre sí. De hecho, estamos rodeados de inventos y avances inspirados en ideas de la naturaleza, aplicados para dar solución a problemas en campos muy diferentes. Por ejemplo, la invención del velcro surgió a partir de un paseo por el campo de un ingeniero francés y sus perros. Mientras salía de caza se fijó en que unas flores con ganchos se quedaban fuertemente adheridas a sus pantalones y al pelaje de sus perros. Como buen inventor, supo ver más allá y pensó que a raíz de ese descubrimiento podría crear un sistema o mecanismo de cierre y fijación basándose en el sistema de la planta. El velcro, revolucionario por su resistencia y por su facilidad para abrirlo, fue rápidamente popularizado por la NASA. A este proceso de búsqueda de similitudes y paralelismos entre un dominio familiar o cercano y otro dominio más desconocido o lejano, a través de la

transferencia de información de un campo a otro, es lo que llamamos razonamiento analógico. El uso de analogías tiene una gran importancia en el pensamiento humano, pues no razonamos de forma analógica únicamente para resolver problemas o reparar en nuevos descubrimientos o inventos. El razonamiento analógico se utiliza en educación cada vez que un profesor compara el modelo del sistema solar, en el que los planetas orbitan alrededor del sol, con el modelo atómico en el que los electrones giran alrededor del núcleo, para facilitar su comprensión. Las analogías también pueden ser utilizadas como instrumento de argumentación en derecho o política. Por ejemplo, el presidente Eisenhower justificó la intervención militar en Vietnam para detener la influencia comunista apelando a la analogía de las fichas de dominó puestas en fila en la que, al caer la primera ficha, uno tiene la certeza de que las demás caerán en cadena. De esta forma, pensó, la derrota de Vietnam supondría la de Indochina, Birmania y Tailandia.

Sin embargo, y aunque usemos el razonamiento analógico en nuestro día a día en una gran variedad de contextos, la investigación demuestra que las personas suelen experimentar dificultades a la hora de transferir información relevante de un contexto a otro de forma espontánea (Gick & Holyoak, 1980, 1983). La mayoría de estudios que han intentado identificar factores que podrían influir en estos fracasos se ha centrado, principalmente, en aspectos que podrían perjudicar el proceso de establecimiento de correspondencias o extrapolación de

información (en inglés *mapping*), que permite la extrapolación de información de un dominio a otro. Sin embargo, no ha recibido la misma atención el estudio de aquellos procesos que influyen en la recuperación de información potencialmente relevante. Dar con una solución apropiada a un problema que requiere razonamiento analógico podría resultar difícil si la información a la que necesitásemos acceder no se encuentra disponible temporalmente. Algunos investigadores han propuesto que la accesibilidad de la información en nuestra memoria es modulada por la actuación de mecanismos de control inhibitorio (Anderson, 2003; Anderson, Bjork, y Bjork, 1994). Estos mecanismos influirían sobre la recuperación reduciendo la accesibilidad de representaciones de memoria que resultan irrelevantes y producen interferencia sobre las que se consideran relevantes en un momento dado (Anderson et al., 1994). Por ejemplo, cuando queremos recordar dónde aparcamos el coche por última vez, dónde dejamos las gafas o recordar el título de una canción que estamos escuchando, debemos evitar la recuperación de otras alternativas que pueden impedir que demos con la información que realmente queremos recordar.

A la hora de resolver un problema, podría ocurrir que las soluciones óptimas resulten poco accesibles precisamente porque presentan un bajo nivel de activación al haber sido objeto del control inhibitorio, lo que daría lugar a una peor resolución del problema. Por ejemplo, en una situación de *brain storming*, la discusión de ideas no

apropiadas puede llevar a la inhibición de las apropiadas y hacerlas menos accesibles. De esta forma, los mecanismos de control inhibitorio que reducen el nivel de activación de información irrelevante (Levy et al., 2008) podrían también afectar de forma negativa el rendimiento en tareas de resolución de problemas, si la información previamente inhibida se convierte en la que se necesita recuperar como solución apropiada en un determinado momento. En este sentido, el objetivo general de este proyecto es el de determinar el papel que tienen la memoria y los procesos de inhibición en la resolución de problemas que requieren razonamiento analógico.

Uno de los primeros objetivos de nuestra investigación consistió en estudiar los índices conductuales de los mecanismos de control inhibitorio en la accesibilidad de las representaciones en memoria durante la resolución de problemas. Con este fin, realizamos una serie de experimentos en los que manipulamos la accesibilidad de la información que posteriormente sería relevante para una tarea de resolución de problemas de razonamiento analógico. Para determinar si la información relevante previamente inhibida podría afectar negativamente al desempeño en la resolución de analogías utilizamos una adaptación del paradigma de práctica en la recuperación con el que este tipo de mecanismos de control inhibitorio han sido ampliamente estudiado (Anderson, Bjork y Bjork, 1994). Durante una primera fase de estudio, los participantes memorizan pares de palabras formados por

una categoría y diferentes ejemplares (BA-Balanza, BA-Batalla, CA-Canario). Posteriormente, en la fase de práctica en la recuperación, se les pide que recuerden la mitad de los ejemplares de la mitad de las categorías (BA-Bal___) a lo largo de una serie de ensayos. Tras la realización de una prueba distractora, se realiza una tarea de recuerdo o reconocimiento del total de los ejemplares estudiados en la primera fase (BA-Bal___). La recuperación repetida de ciertos ejemplares suele conllevar un peor recuerdo/reconocimiento de los ítems no practicados pertenecientes a la misma categoría en comparación con los ítems control. Este efecto, conocido como 'olvido inducido por la recuperación' (OIR), se ha interpretado como consecuencia de un mecanismo de inhibición que actuaría durante la práctica de la recuperación para ayudar a seleccionar los trazos de memoria objetivo. En nuestros experimentos, en lugar de una prueba de memoria final, se creó una prueba de razonamiento analógico del tipo 'A es a B como C es a ?', en la que hay que identificar la relación entre la pareja A y B y buscar una palabra que reproduzca la misma relación entre C y D. Las analogías fueron creadas de forma que la mayoría de ellas podían ser resueltas con uno de los ejemplares estudiados al comienzo del experimento (PAZ es a PALOMA como JUSTICIA es a … cuya solución es la palabra BALANZA). De esta forma podríamos conocer si los mecanismos inhibitorios pueden jugar un papel importante en la modulación de la accesibilidad a las distintas alternativas en la resolución de analogías

reduciendo la activación de información relevante y dificultando dar como respuesta la solución apropiada. En efecto, encontramos que una menor accesibilidad a soluciones potenciales dificultaba el desempeño en el razonamiento analógico. Además, esto ocurría incluso cuando los participantes no eran conscientes de la relación entre ambas tareas. Por tanto, los mecanismos de control inhibitorio que reducen el nivel de activación de trazos episódicos pueden también afectar de forma negativa el rendimiento en tareas de resolución de problemas. Esto ocurriría en situaciones en la que la información previamente inhibida se convierte en la que se necesita recuperar como solución apropiada en un determinado momento.

El segundo objetivo fue el de examinar mediante medidas electrofisiológicas de la actividad cerebral los correlatos neurales de los mecanismos que producirían el efecto de inhibición. La utilización de esta técnica permite analizar patrones cerebrales provocados por la ocurrencia de un suceso con una alta resolución temporal, que se conoce como registro de potenciales evocados. Se considera que los potenciales evocados podrían ser indicadores de procesos o subprocesos cognitivos en atención, memoria o comprensión del lenguaje. Por la tanto, se siguió un procedimiento similar a los anteriores experimentos para manipular el acceso a posibles soluciones que se necesitarían posteriormente para resolver analogías. Paralelamente, se registró la actividad cerebral durante la fase de práctica en la recuperación (en la que se piensa que

estos mecanismos de control actuarían) y durante la prueba de resolución de analogías. En la fase de práctica en la recuperación los resultados mostraron que la presentación de la categoría (p.e. BA) por primera vez elicitaba una mayor positividad en el componente FN400 en regiones frontales anteriores y parietales izquierdas en comparación con cuando se presentaba por segunda y tercera vez. El componente FN400 ha sido relacionado con la reactivación de memorias asociadas a una clave y con detección de la interferencia (Hellerstedt & Johansson, 2014). Los cambios en la amplitud de este componente correlacionaban, además, con un peor desempeño posterior durante el test de analogías. En conjunto, estos resultados sugieren que a medida que la categoría se presentaba, los niveles de interferencia se veían reducidos. Esta disminución de la interferencia es consistente con la perspectiva inhibitoria en términos de control. Por otra parte, quisimos investigar los correlatos neurales de estos procesos de regulación de la memoria en el test de analogías. La modulación de la accesibilidad durante la prueba de memoria influyó en los patrones de respuesta electrofisiológica asociados a la generación de soluciones a las analogías. La generación de soluciones que habían sido previamente inhibidas mostraba amplitudes similares a la generación de soluciones que no se habían presentado con anterioridad en el contexto del experimento. No obstante, sí que se observaban diferencias en amplitud entre la producción de soluciones control y nuevas. Estos resultados indican que la práctica en la

recuperación moduló la accesibilidad de las representaciones de memorias afectando al razonamiento analógico. Además, el hecho de que estos cambios en el patrón de procesamiento únicamente se reflejaran durante la fase en la que los participantes debían dar una solución a la analogía y no afectasen a la fase de *mapping*, indica que los procesos de control de memoria afectarían selectivamente a la recuperación de la respuesta y no interferiría en los procesos de establecimiento de múltiples correspondencias.

Los estudios de neuroimagen coinciden en destacar la implicación de regiones como el córtex prefrontal dorsolateral (DLPFC) con la supresión de recuerdos y el control inhibitorio (Kuhl et al., 2007; Wimber et al., 2009). No obstante, el uso del registro de la actividad cerebral solo proporciona información sobre como correlaciona la actividad cerebral con ciertas funciones cognitivas. Es por ello que en nuestro último experimento teníamos el objetivo de comprobar mediante el uso de la tDCS (estimulación transcraneal por corriente continua), una técnica de neuromodulación, si la alteración de la actividad cortical de regiones implicadas en la inhibición de recuerdos podría afectar al desempeño de la resolución de problemas que requiriesen razonamiento analógico. Las tDCS permite cambiar la excitabilidad cortical y, por ende, establecer relaciones causales entre la actividad cerebral y ciertos procesos psicológicos. Por tanto, se utilizó la tDCS para estudiar si el DLPFC (del hemisferio derecho) se encuentra

directamente implicado en la reducción de la accesibilidad a palabras que podrían funcionar como posibles soluciones en problemas que requieren razonamiento analógico. Siguiendo un procedimiento similar al de estudios previos, se administró estimulación tDCS catodal o Sham en dicha región. Por una parte, en el grupo de estimulación placebo encontramos que la manipulación de la accesibilidad de la información afectaba la resolución de problemas que requería dicha información posteriormente, replicando resultados anteriores. Sin embargo, en el grupo de estimulación catodal (que previsiblemente produce una disminución de la excitabilidad cortical) la manipulación de la accesibilidad de la información relevante no produjo ningún cambio en la resolución de problemas. Estos resultados nos llevan a pensar que, tal y como demuestran estudios de neuroimagen previos, el DLPFC estaría implicado en la implementación de control inhibitorio que también parece influir en el desempeño en la resolución de analogías. Además, el hecho de que la estimulación no beneficiase o perjudicase el desempeño general en el razonamiento analógico confirma que la actuación del DLPFC parece modular de forma específica la recuperación de información relevante sin influir sobre procesos de *mapping*.

Al enfrentamos a un problema, con frecuencia solemos recurrir a información que ya se utilizó para para solucionar o entender un problema similar. El acceso a la memoria es crucial en este tipo de razonamiento inductivo, puesto que la solución de problemas requiere

recordar soluciones aplicadas en situaciones similares con anterioridad, reunir información y explorar diferentes alternativas que se puedan aplicar de forma novedosa para resolverlo. Este trabajo amplía el estudio del papel que juegan los procesos de control de la memoria en la modulación de la accesibilidad de información relevante y su repercusión en la resolución de problemas de razonamiento analógico. Teniendo en cuenta el conjunto de datos presentados en esta tesis, podemos concluir que aunque la inhibición sea un mecanismo de control que ayuda a recuperar con eficacia ciertos contenidos o experiencias que se requieren en un momento determinado, también puede repercutir en tareas posteriores si la información inhibida se requiere en una tarea posterior.

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Appendices

Appendix I. Orthography-Based Word Categories and analogical problems used in Experiments 1, 2 and 4.

Appendix II. Orthography-Based Word Categories and analogical problems used in Experiment 3.

Appendix I. Orthography-Based Word Categories and analogical problems used in Experiments 1, 2 and 4.

Practiced Status	BA	Analogy	MA	Analogy
Rp+/Nrp+/Np+ items	Bambú	ARDILLA es a BELLOTA como OSO PANDA es a…	Maquillaje	LIBRO es a BIBLIOTECA como COLORETE es a...
	Balanza	PAZ es a PALOMA como JUSTICIA es a…	Marinero	PARQUE es a NIÑOS como BARCO es a…
	Bañera	DORMIRSE es a CAMA como LAVARSE es a…	Matanza	LIEBRE es a CACERÍA como CERDO es a…
Rp-/Nrp-/Np- items	Bandera	GOLPEAR es a MARTILLO como IZAR es a…	Madurez	AVARICIA es a GENEROSIDAD como INFANTILISMO a...
	Basura	DISPUTA es a PELEA como DESPERDICIOS es a…	Maleta	ENCICLOPEDIA es a LIBRO como EQUIPAJE es a…
	Batalla	BERLÍN es a MURO como TRAFALGAR es a…	Manual	DIVERSIÓN es a ABURRIMIENTO como AUTOMÁTICO es a…

Practiced Status	DE	Analogy	CA	Analogy
Rp+/Nrp+/Np+ items	Detective	BISTURÍ es a CIRUJANO como LUPA es a…	Canario	PASTOR es a ALEMÁN como PLÁTANO es a...
	Delito	HEPATITIS es a ENFERMEDAD como HOMICIDIO es a…	Capitán	CIUDAD es a ALCALDE como BARCO es a…
	Debate	ARMA es a GUERRA como ARGUMENTO es a...	Caracol	CABALLO es a CEBRA como BABOSA a…
Rp-/Nrp-/Np- items	Desastre	IRA es a FURIA como CATÁSTROFE es a…	Cabello	CIELO es a TOCINO como ÁNGEL es a…
	Deporte	PASTEL es a REPOSTERÍA como ATLETISMO es a…	Camarero	MUEBLE es a CARPINTERO como CÓCTEL es a…
	Democracia	LIBERTAD es a ESCLAVITUD como DICTADURA es a…	Catedral	PENSIÓN es a HOTEL como IGLESIA es a…

Practiced Status	PE	Analogy	FA	Analogy
Rp+/Nrp+/Np+ items	Pedazo	ESTUDIANTE es a ALUMNO como TROZO es a...	Fauna	ESTRELLA es a CONSTELACIÓN como ANIMAL es a...
	Pesimismo	ALEGRÍA es a ENTUSIASMO como NEGATIVIDAD a…	Fallo	SUEÑO es a REALIDAD como ACIERTO es a...
	Petición	PROHIBICIÓN es a NEGACIÓN como SOLICITUD es a...	Farmacia	FRUTA es a MERCADO como MEDICAMENTO es a…
Rp-/Nrp-/Np- items	Pelota	CUBO es a DADO como ESFERA es a...	Fábrica	HOSTELERÍA es a RESTAURANTE como INDUSTRIA es a…
	Península	BALEAR es a ARCHIPIÉLAGO como IBÉRICA es a…	Fantasía	RISA es a COMEDIA como DRAGÓN es a…
	Pereza	GLOTONERÍA es a GULA como VAGUEZA es a...	Famoso	ROBUSTO es a GORDO como CÉLEBRE es a…

Practiced Status	DI	Analogy	RE	Analogy
Rp+/Nrp+/Np+ items	Digestión	MECÁNICO es a REPARACIÓN como ESTÓMAGO es a…	Rebaño	PECES es a BANCO como OVEJAS es a…
	Dilema	DESEO es a ANHELO como PROBLEMA es a...	Receta	LAVADORA es a INTRUCCIONES como COMIDA es a…
	Divorcio	ALIVIO es a ANGUSTIA como MATRIMONIO es a…	Relámpago	NUBLADO es a LLUVIA como TRUENO es a...
Rp-/Nrp-/Np- items	Diciembre	SEMANA es a DOMINGO como AÑO es a...	Regalo	FATIGA es a CANSANCIO como OBSEQUIO es a…
	Difunto	REY es a MONARCA como FALLECIDO es a...	Restaurante	CATÁLOGO es a SUPERMERCADO como MENÚ es a…
	Diseño	CANCIÓN es a COMPOSICIÓN como ROPA a…	Retrato	CAMA es a LECHO como FOTOGRAFÍA es a...

Practiced Status	TA	Analogy
Rp+/Nrp+/Np+ items	Tango	BRASIL es a SAMBA como ARGENTINA es a...
	Tarjeta	TRÁFICO es a MULTA como FÚTBOL es a…
	Tacto	SONIDO es a OÍDO como CARICIA es a…
Rp-/Nrp-/Np- items	Taller	FLOR es a CAMPO como HERRAMIENTA es a…
	Taza	FLOR es JARRÓN como CAFÉ es a…
	Tabaco	PROTEÍNA es a POLLO como NICOTINA es a…

Appendix II. Orthography-Based Word Categories and analogical problems used in Experiment 3.

List 1

Practiced Status	BA	Analogy	MA	Analogy
Rp+/Nrp+/Np+ items	Bambú	ARDILLA es a BELLOTA como OSO PANDA es a…	Maquillaje	LIBRO es a BIBLIOTECA como COLORETE es a...
	Balanza	PAZ es a PALOMA como EQUILIBRIO es a…	Marinero	PARQUE es a NIÑOS como BARCO es a…
	Bañera	DORMIRSE es a CAMA como LAVARSE es a…	Matanza	LIEBRE es a CACERÍA como CERDO es a…
Rp-/Nrp-/Np- items	Bandera	PELIGRO es a CALAVERA como PATRIA es a…	Madurez	AVARICIA es a GENEROSIDAD como INFANTILISMO a...
	Basura	DISPUTA es a PELEA como DESPERDICIOS es a…	Maleta	ENCICLOPEDIA es a LIBRO como EQUIPAJE es a…
	Batalla	AVAL es a GARANTÍA como COMBATE es a…	Manual	DIVERSIÓN es a ABURRIMIENTO como AUTOMÁTICO es a…

Practiced Status	DE	Analogy	CA	Analogy
Rp+/Nrp+/Np+ items	Detective	BISTURÍ es a CIRUJANO como LUPA es a…	Canario	PASTOR es a ALEMÁN como PLÁTANO es a...
	Delito	HEPATITIS es a ENFERMEDAD como HOMICIDIO es a…	Capitán	CIUDAD es a ALCALDE como BARCO es a…
	Debate	ARMA es a GUERRA como ARGUMENTO es a...	Caracol	CABALLO es a CEBRA como BABOSA a…
Rp-/Nrp-/Np- items	Desastre	IRA es a FURIA como CATÁSTROFE es a…	Cabello	CIELO es a TOCINO como ÁNGEL es a…
	Deporte	BALLENA es a CETÁCEO como ESGRIMA es a…	Camarero	MUEBLE es a CARPINTERO como CÓCTEL es a…
	Democracia	LIBERTAD es a ESCLAVITUD como DICTADURA es a…	Catedral	CHOZA es a EDIFICIO como CAPILLA es a…

Practiced Status	PE	Analogy	FA	Analogy
Rp+/Nrp+/Np+ items	Pedazo	ESTUDIANTE es a ALUMNO como TROZO es a...	Fauna	ESTRELLA es a CONSTELACIÓN como ANIMAL es a...
	Pesimismo	ALEGRÍA es a ENTUSIASMO como NEGATIVIDAD a…	Fallo	SUEÑO es a REALIDAD como ACIERTO es a...
	Petición	PROHIBICIÓN es a NEGACIÓN como SOLICITUD es a...	Farmacia	FRUTA es a MERCADO como MEDICAMENTO es a…
Rp-/Nrp-/Np- items	Pelota	CUBO es a DADO como ESFERA es a...	Fábrica	HOSTELERÍA es a RESTAURANTE como INDUSTRIA es a…
	Península	BALEAR es a ARCHIPIÉLAGO como IBÉRICA es a…	Fantasía	RISA es a COMEDIA como DRAGÓN es a…
	Pereza	GLOTONERÍA es a GULA como VAGANCIA es a...	Famoso	ROBUSTO es a GORDO como CÉLEBRE es a…

Practiced Status	DI	Analogy	RE	Analogy
Rp+/Nrp+/Np+ items	Digestión	MECÁNICO es a REPARACIÓN como ESTÓMAGO es a…	Rebaño	REY es a PUEBLO como PASTOR es a…
	Dilema	DESEO es a ANHELO como PROBLEMA es a...	Receta	MONTAJE es a INSTRUCCIONES como COCINAR es a…
	Divorcio	ALIVIO es a ANGUSTIA como MATRIMONIO es a…	Relámpago	NUBLADO es a LLUVIA como TRUENO es a...
Rp-/Nrp-/Np- items	Diciembre	SEMANA es a DOMINGO como AÑO es a...	Regalo	FATIGA es a CANSANCIO como OBSEQUIO es a…

Difunto	REY es a MONARCA como FALLECIDO es a...	Restaurante	CATÁLOGO es a SUPERMERCADO como MENÚ es a…
Diseño	CANCIÓN es a COMPOSICIÓN como ROPA a…	Retrato	CAMA es a LECHO como FOTOGRAFÍA es a...

Practiced Status	TA	Analogy
Rp+/Nrp+/Np+ items	Tango	BRASIL es a SAMBA como ARGENTINA es a...
	Tarjeta	TRÁFICO es a MULTA como FÚTBOL es a…
	Tacto	SONIDO es a OÍDO como CARICIA es a…
Rp-/Nrp-/Np- items	Taller	FLOR es a CAMPO como HERRAMIENTA es a…
	Taza	FLOR es JARRÓN como CAFÉ es a…
	Tabaco	PROTEÍNA es a POLLO como NICOTINA es a…

Practiced Status	JU	Analogy	SO	Analogy
Rp+/Nrp+/Np+ items	Judío	IMÁN es a MUSULMÁN como RABINO es a…	Sótano	CIMA es a PIE como ÁTICO es a...
	Jugador	DENTADURA es a DIENTE como EQUIPO es a...	Sorbo	COMIDA es a BOCADO como BEBIDA es a...
	Jungla	CAMINO es a SENDA como SELVA es a...	Socio	ORQUESTA es a MÚSICO como ASOCIACIÓN es a...
Rp-/Nrp-/Np- items	Justicia	PARLAMENTO es a POLÍTICA como TRIBUNAL es a...	Sombrero	SANDALIAS es a TACONES como GORRA es a…
	Juvenil	CRUELDAD es a PIEDAD como SENIL es a...	Sofá	DESPERTADOR es a MESITA como COJÍN es a...
	Jueves	NOVIAZGO es a MATRIMONIO como MIÉRCOLES es a...	Soldado	PÚBLICO es a ESPECTADOR como TROPA es a…

Practiced Status	VI	Analogy	VE	Analogy
Rp+/Nrp+/Np+ items	Viajero	ZAPATO es a CALZADO como TROTAMUNDOS es a...	Veneno	MOFETA es a OLOR como SERPIENTE es a...
	Vinagre	ANCHOA es a SALMUERA como PEPINILLO es a…	Vestuario	CAMA es a DORMITORIO como TAQUILLAS es a...
	Violín	TROMBÓN es a TROMPETA como CONTRABAJO es a...	Veterinario	MUEBLE es a CARPINTERO como ANIMAL es a...
Rp-/Nrp-/Np- items	Víctima	ABUELO es a NIETO como AGRESOR es a...	Vehículo	QUESO es a LÁCTEO como FURGÓN es a...

Vídeo	RADIO es a AUDIO como TELEVISIÓN es a...	Vela	CADENA es a CANDADO como MÁSTIL es a…
Vivienda	BÍCEPS es a MÚSCULO como APARTAMENTO es a...	Vergüenza	BLANCO es a MIEDO como COLORADO es a...

List 2

Practiced Status	SU	Analogy	LO	Analogy
Rp+/Nrp+/Np+ items	Suavidad	LIMÓN es a ACIDEZ como SEDA es a...	Loro	DORMIR es a MARMOTA como REPETIR es a…
	Sugerencia	IMPACTO es a COLISIÓN como RECOMENDACIÓN es a...	Logro	DIVULGACIÓN es a DIFUSIÓN como ÉXITO es a…
	Suciedad	SONRISA es a FELICIDAD como MANCHA es a...	Lotería	ANTIFAZ es a MÁSCARA como TÓMBOLA es a...
Rp-/Nrp-/Np- items	Sudor	TRISTEZA es a LÁGRIMA como ESFUERZO es a...	Lobo	CABRA es a OVEJA como PERRO es a...
	Sufrimiento	VICTORIA es a SATISFACCIÓN como DOLENCIA es a...	Locura	SERIEDAD es a FORMALIDAD como DEMENCIA es a...
	Susurro	CICLÓN es a BRISA como GRITO es a...	Longitud	TERMÓMETRO es a TEMPERATURA como REGLA es a...

Practiced Status	LI	Analogy	NO	Analogy
Rp+/Nrp+/Np+ items	Literal	REMOTO es a LEJANO como TEXTUAL es a…	Nocturno	DURADERO es a FUGAZ como DIURNO es a...
	Líder	MAÑOSO es a HÁBIL como CABECILLA es a...	Normativa	ADVERSIDAD es a CONTRATIEMPO como REGLAMENTACIÓN es a...
	Linterna	ÁBACO es a CALCULADORA como ANTORCHA es a…	Notario	PINCEL es a PINTOR como FIRMA es a...
Rp-/Nrp-/Np- items	Limpieza	VERAZ es a SINCERIDAD como HIGIENE es a...	Nobleza	DEVOTO es a CREYENTE como ARISTOCRACIA es a...

	Líquido	ALBOROTO es a RUIDO como FLUIDO es a...	Nostalgia	FUTURO es a PREOCUPACIÓN como PASADO es a…
	Ligero	AFILADO es a PUNTIAGUDO como LIVIANO es a...	Novedad	CARENCIA es a ESCASEZ como PRIMICIA es a…

Practiced Status	**GA**	**Analogy**
Rp+/Nrp+/Np+ items	Gatillo	INCENDIO es a CHISPA como DISPARO es a...
	Gaviota	SELVA es a TUCÁN como COSTA es a...
	Gasolina	VENTILADOR es a ELECTRICIDAD como MOTOR es a...
Rp-/Nrp-/Np- items	Gallina	ASTUTO es a ZORRO como COBARDE es a...
	Ganado	ABEJA es a ENJAMBRE como VACA es a...
	Garganta	OTITIS es a OÍDO como AMIGDALITIS es a...